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MODELING URBAN ATMOSPHERIC TEMPERATURE PROFILES

by

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MACKENZIE LEO DAVIS

Thesis

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MODELING URBAN ATMOSPHERIC TEMPERATURE PROFILES

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The possibility of modeling the effect of the urban heat island on atmospheric stability was investigated.

After establishing the fact that the city of Fort Wayne, Indiana did significantly increase the nocturnal atmospheric temperature over that of its rural environs, some consideration was given to the reasons for this effect. It was found that heat resulting from fuel consumption and the more efficient heat storage properties of the city structure contributed approximately 30 percent more heat to the urban environment than was available to the rural environment. Other sources of heat energy did not appear to be of significant consequence in effecting the urban-rural temperature difference.

The analysis of the vertical temperature profiles taken over Fort Wayne (Hilst and Bowne, 1966) showed a definite alteration of atmospheric stability.

A model law based on the Monin-Obukhov scale length of turbulence was developed for use in comparing the model and prototype in autogenous atmospheric simulation.

A model of the City of Fort Wayne, Indiana was constructed in an open, flat field in Central Illinois in an attempt to simulate the effect of the nocturnal heat island on atmospheric stability. The model to prototype scales were 1:1000 in the horizontal and approximately 1:40 in the vertical.

Temperature measurements in the model were compared with existing data for the Fort Wayne complex. Moderate success was achieved in reproducing stability variation across the complex and the model law was shown to relate the model experiments to the prototype.

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A = area, km^2

a = heat contribution from automotive fuel consumption, ly min^{-1}

Bo = Boussinesq number

C = geostrophic drag coefficient

C_p = specific heat at constant pressure, g-cal g^{-1} $^{o}K^{-1}$

D = temperature difference, ^{o}C

d = diameter of sensor, in.

E = latent heat flux, ly min^{-1}

e = absolute humidity, mm of Hg

Fr = Froude number

f = Coriolis parameter = $2\Omega \sin \varphi$

G = heat flux into surface, ly min^{-1}

g = acceleration due to gravity, m sec^{-2}

H = turbulent heat flux, ly min^{-1}

h = vertical dimension of object, m

i = heat contribution from industrial processes, ly min^{-1}

k = von Karman's constant

K_H^* = eddy diffusivity of heat, m^2 sec^{-1}

K_M^* = eddy viscosity, m^2 sec^{-1}

K_L, K_U = scale factors for length, wind speed, etc.

L = characteristic length, m

L_* = scale length of turbulence, m

m = heat contribution from metabolic activity, ly min^{-1}

N = cloudiness

p = heat contribution from power plants, ly min^{-1}

Q = heat flux from human activity, ly min^{-1}

Q_* = emission rate of gaseous pollutant, g m^{-3}

q = relative velocity, m sec^{-1}

R = distance between measurements, km

R_D = diffuse radiation, ly min^{-1}

Re = Reynolds number

Rf = Richardson number (flux)

Ri = Richardson number (gradient)

R_L = long wave atmosphere counter radiation, ly min^{-1}

R_N = net radiation, ly min^{-1}

Ro = Rossby number

Ro_s = "surface" Rossby number

R_s = solar radiation, ly min^{-1}

S = spectral intensity

s = heat contribution from space heating, ly min^{-1}

S_x^2, S_y^2 = standard error of estimate

T = temperature, ^oC or ^oK

$T_{10\ cm}$ = temperature at elevation of 10 cm, ^oC

U = characteristic velocity, m sec^{-1}

$\bar{u}$ = average wind speed (in x direction at specified level), m sec^{-1}

u_* = friction velocity, m sec^{-1}

V = rate of evaporation, g m^{-2} sec^{-1}

$V_{g,o}$ = geostrophic wind at ground level

$X_{(x,y,z)}$ = concentration of gaseous pollutant at coordinate (x,y,z)

x, y, z = coordinates (+ x oriented in direction of $\bar{u}$)

z_o = roughness parameter, m

α = albedo

β, ϵ, ϕ = angles

Γ = dry adiabatic lapse rate, $^oC\ m^{-1}$

Δ = incremental difference

θ = potential temperature, ^oC

λ = thermal conductivity, g-cal cm $hr^{-1}\ cm^{-2}\ {}^oC^{-1}$

μ = absolute viscosity, kg $m^{-1}\ sec^{-1}$

ν = kinematic viscosity, $m^2\ sec^{-1}$

ρ = density, kg m^{-3}

τ = fluid shear, kg $m^{-1}\ sec^{-1}$

τ_* = time constant, sec

σ = Stephen Boltzman constant

$\sigma x, \sigma y, \sigma z$ = variances of pollutant concentration in x, y, and z directions, m

φ = latitude, degrees

Ω = angular velocity, sec^{-1}

CHAPTER I

INTRODUCTION

The trend of human migration has been toward the increasing consolidation of populations. With industrialization came accelerated urbanization. The result, in the United States, has been that 53 percent of the nation's population is concentrated on 0.7 percent of the nation's land (Davis, 1965). This migration has produced both biological and climatological effects of notable consequence.

Every vital index available indicates that our major cities are very likely the healthiest environment ever developed for human habitation. Although studies of chronic illness have thus far produced no substantial evidence, the major air pollution episodes have dramatically indicated that urban environments may be less than ideal. Sophisticated statistical techniques have revealed a number of "minor" episodes (Bradley, 1966; McCarroll and Bradley, 1966) which with further investigation may prove to be a rather common occurrance in urban environments.

A concomitant of the episodes, both major and minor, has been a particular set of meteorological phenomena. The peaks in mortality are associated with periods of low wind speeds and stagnating high pressure cells. Unlike the experience of the major episodes of London and Donora, fog is not a necessary part of the minor episode (McCarroll and Bradley, 1966).

Urban biometeorologists have been devoting increased effort to the problem of predicting not only conditions conducive to episodes but also patterns of pollution on all ranges of time scales. One of

the intrinsic difficulties of the problem has been the description of urban meteorology and climatology. Unfortunately, the considerable effort which has been expended in describing urban climatology has been limited to an extremely shallow layer above the surface. Although the problem of discharged pollutants also falls in a comparatively shallow layer ($\sim$200m), it is an order of magnitude greater than the one for which the vast majority of information is available. This deficiency is primarily the result of economic restrictions in taking vertical profiles rather than a lack of concern or technological capability. The recent introduction of television towers has alleviated the problem slightly, but spatial variations are still difficult to describe.

As a result of the difficulty in describing the atmosphere above the city surface, the diffusion equations have proven to be less than satisfactory. Improvement in the predictions of pollutant distribution in the urban area can possibly be achieved by improving measurements of stability. Increasing the complexity of either the diffusion model or the source inventory does not appear to be warranted until air pollutant field measurements with lower thresholds and greater accuracy can be obtained on a routine basis (Turner, 1964).

With the recognition of these problems, meteorologists have begun basic field studies to augment and quantify their knowledge of the meteorology of the urban environment. The results of these investigations will offer order of magnitude estimates of the dispersion variables. Generalization of these results to other cities and situations will prove difficult because the results will be strongly

dependent on the details of the topography and configuration of the urban sources. The fact that considerable effort and money is involved in obtaining only sparse information for each locality makes it imperative that additional investigating techniques be considered. This thesis is the culmination of an effort to test one of the suggested alternative techniques, namely, modeling.

CHAPTER II

LITERATURE REVIEW

A. Introduction

In order to test a model one must compare the results obtained from it with those available from prototype studies. Although the model is of primary concern, the behavior of the prototype is no less important. The literature which was reviewed, therefore, included the areas of urban climatology and atmospheric modeling.

B. Historical Background

Howard's (1818; 1820) report of the urban-rural temperature disparity of London was the first scientific observation of urban climatology. His explanation for the warmth of the city over its rural environs (the "heat island") was related to the following five characteristics: the structure of the city; the crowded population; consumption of fuel; reduced air circulation and lower humidity. At irregular intervals throughout the 19th century other European investigators confirmed the general impression of the urban heat island without adding significantly to the definition of cause.

Next to attract the attention of investigators was atmospheric pollution (Angot, 1891). Subsequently precipitation (Hellmann, 1892), humidity (Kremser, 1908), wind (Kremser, 1909) and radiation (Besson, 1922) were taken under consideration.

The primary research tool of these investigations and of many that followed was the observational record of weather shelters.

Great impetus was given to the study of urban climatology by Schmidt's (1927) novel application of the automobile. With the automobile as a traversing tool he was able to take near simultaneous measurements at a great number of points throughout the city. The economic, instrumental and manpower problems of setting up a satisfactory observational grid to provide a broad picture of the variations of a climatic element were thus overcome. These "measuring trips" remain to this day one of the more frequently used methods for investigation.

The monograph, Das Stadtklima, written by P. A. Kratzer in 1937 and revised in 1956, remains as the basic collection of literature on urban climatology. Reference to this work should be made for a more thorough discussion of the historical sketch given above. (The several aspects of urban climatology will be discussed in the following sections.)

C. The Climate of Cities

1. Wind

The urban area affects the wind system through two modes. With winds of moderate speed the primary effect of the urban area may be a change in frictional drag from the surrounding countryside. Under near calm conditions, the thermal action of the city (the heat island) may give rise to a city wind system.

If one assumes a vertical wind profile in which the wind speed increases in direct proportion to the logarithm of height, then

the wind profile may be formulated mathematically with the "logarithmic wind law":

$$\bar{u} = \frac{u_*}{k} \ln \frac{z}{z_o} \tag{1}$$

where $\bar{u}$ = average wind speed in x direction at level z, m sec^{-1}

u_* = friction velocity, m sec^{-1}

z = height above surface, m

k = von Karman's constant, ~ 0.4

z_o = roughness parameter, m

The roughness parameter (z_o) is a scale factor for height and depends, among other parameters, on the height and density of the spacing of the surface elements (Kutzbach, 1961).

The relative roughness of the city in comparison with its environs can be seen in Table 1.

TABLE 1

SOME REPRESENTATIVE ROUGHNESS PARAMETERS

Surface	z_o, m	Source
Ice	0.0001	Kutzbach (1961)
Mown Grass (1-5 cm)	0.001 to 0.01	Pasquill (1962)
Corn	0.002 to 0.04	Plate & Quraishi (1965)
Wheat	0.03 to 0.05	Plate & Quraishi (1965)
Forest	0.3 to 2	Johnson (1965)
Minneapolis-St. Paul	2	Deland & Binkowski (1966)
London (Canada)	2.3	Davenport (1967)
Tokyo	4	Shiotani & Yamamoto (1950)

The change in frictional drag caused by the city is relative and highly dependent on the nature of the surrounding surfaces as well as the vertical structure of the city.

As a general consequence of the increased roughness of the city, there is a decrease in the wind speed. This is reflected, for example, in the difference in wind speeds between La Guardia Airport (Elev. 25 m) and Central Park (Elev. 18.9 m) in New York.

TABLE 2

SEASONAL AVERAGE WIND SPEEDS FOR NEW YORK[a]

Season	La Guardia m sec^{-1}	Central Park m sec^{-1}	Wind Speed Difference corrected for elevation m sec^{-1}
Spring	5.6	4.4	1.0
Summer	4.7	3.6	1.0
Fall	5	3.8	1.0
Winter	6.5	5.0	1.3

[a]After Landsberg (1956)

The reduced wind speed is reflected in vertical wind profiles as well as the "surface" observations. Figure 1 is an average of the data from 73 wind profiles taken at two tower locations in Fort Wayne, Indiana (Hilst and Bowne, 1966). The rural tower was always upwind of the urban tower.

The next wind consideration is the urban effect on turbulence. Generalizations of turbulence behavior are at best hazardous due to the many interrelated factors which play a role. Turbulence data for an urban-rural configuration are not generally available and in particular not as a climatic summary. The discussion, therefore, will be limited to deductions from other sources.

Panofsky and Deland (1959) have made several generalizations about turbulent energy spectra. For a constant roughness (z_o) they

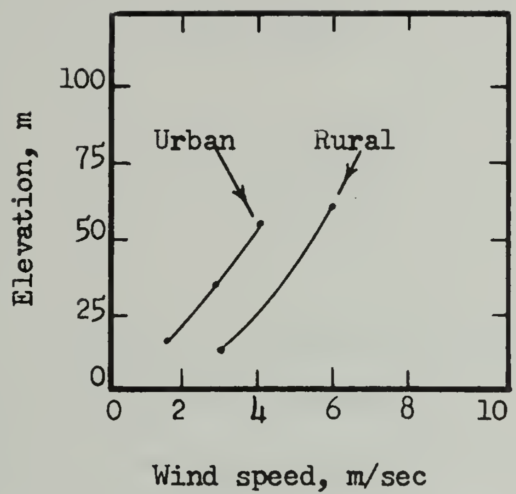

FIGURE 1. URBAN AND RURAL WIND PROFILES FORT WAYNE, INDIANA (After Hilst and Bowne, 1966)

found a change in spectral intensity from S to S' to be related to a change in mean wind speed from $\bar{u}$ to $\bar{u}'$ in the following manner:

$$\frac{S}{S'} \approx \frac{\bar{u}^2}{\bar{u}'^2} \quad . \tag{2}$$

In contrast, it was found that for a constant wind speed and elevation (z), the spectral intensity was related to the roughness parameter (z_o) in the following manner:

$$\frac{S}{S'} \approx \left(\frac{\ln \frac{z}{z'_o}}{\ln \frac{z}{z_o}} \right)^2 \quad . \tag{3}$$

One may note the dependency on roughness which suggests that increased roughness increases the spectral intensity.

The lower frequencies of the lateral velocity spectra are strongly affected by stability indicating that the energy at these frequencies is essentially convective in origin. At frequencies greater than 150 cycles per hour, the dependence on lapse rate is replaced by the dependence on wind speed. In the case of the longitudinal spectra the effect of stability is much weaker. As illustrated in Figure 2 the total energy decreased as rapidly in a stable atmosphere. The effect of the city is to present a rougher surface and less stable atmosphere than the surrounding environs. Thus, it is concluded that the total turbulent energy increases over that found in the rural environs. Graham (1968) found this to be true for a limited number of observations taken at night over Fort Wayne.

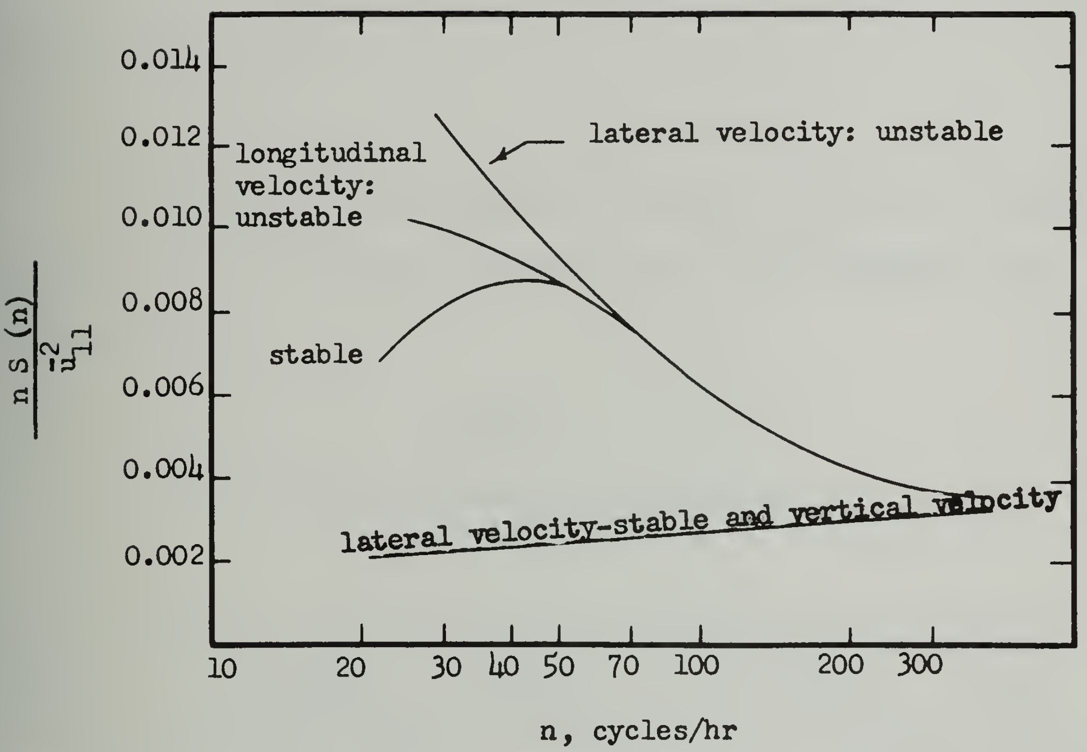

FIGURE 2. SCHEMATIC REPRESENTATION OF TURBULENCE SPECTRA (After Panofsky and Deland, 1959)

The much discussed thermally generated wind of the city (caused by rising of the warmer city air when the mascroscale synoptic situation yields a calm) is not well documented. Chandler (1960) and Pooler (1963) report a general surface inflow at the urban periphery under this condition, but the structure of the city appears to inhibit its development.

2. Precipitation

The opinion of climatologists (Kratzer, 1956) is that cities generally increase the amount of precipitation. Some examples are listed in Table 3.

TABLE 3

URBAN-RURAL PRECIPITATION PATTERNS

City	Urban Precip., cm	Rural Precip., cm	Difference cm	Source
Chicago, Ill.	84.0	80.0	4.0	Kratzer (1956)
St. Louis, Mo.	97.8	96.2	1.6	Kratzer (1956)
Champaign-Urbana, Ill.	85.8	75.6	10.2	Changnon (1961)

In these areas there is a general west-to-east increase in precipitation (based on First Order Station data). This increase amounts to .08 cm of precipitation per km. For Champaign-Urbana this accounts for only 0.64 cm of the observed urban-rural difference (Changnon, 1961). Most climatic precipitation studies reveal a

maximum in the total precipitation at the center or downwind side of the city.

The cities' contribution of condensation nuclei, thermal lifting and increased turbulence have all been suggested as dominant effects. As in most meteorological analyses, the variability of precipitation is probably highly dependent on local circumstances. Changnon (1961) argues convincingly that for Champaign-Urbana the turbulence effect is dominant (because of a relative lack of nuclei sources and the rather small thermal effects of the city.)

3. Humidity

Kremser's (1908) early work on the subject of humidity reflects the general effect of the city in reducing humidity. (Table 4).

TABLE 4

URBAN-RURAL RELATIVE HUMIDITY[a]

City	Relative Humidity Difference %
Vienna	4
Berlin	6
Trier	6
Cologne	6
Breslau	6
Munich	5.5

[a]From Kremser (1908)

In addition to the increase in urban temperatures, the lack of ground moisture (because of the rapid runoff in the built-up areas), and of plant transpiration are recognized as processes contributing to the differential. (It may be noted that the cities' dryness contributes to an absolute increase in temperature, thus completing a cycle.)

4. Radiation

The general effect of the city's atmosphere is to diminish incoming solar and sky radiation. The reduction amounts to between 10 percent and 40 percent depending on the amount of vapor and particulate pollution (Geiger, 1965). This reduction takes two forms. Solar radiation intensity is diminished, and the duration of sunshine is reduced. Both of these factors have been related to air pollution. Figure 3, taken from Ashworth (1935), shows the weekly cycle of radiation intensity which coincides with industrial activity and, by presumption, air pollution emissions. Brooks (1951) has shown that, in London, the decrease in hours of sunshine is directly related to increasing particulate pollution as measured by settleable particulates (Figure 4).

During the major portion of the year the difference between city and farmland albedo is, in the United States, non-existant. (See Table 5). The exception occurs when there is a snow cover. Kung, Bryson and Lenschow (1964) have shown that with only 2.5 cm of snow the farmland albedo is effectively doubled. In contrast it appears from their figures that between 6 and 8 cm of snow are required to produce the same alteration in the city. It is surmized that this is

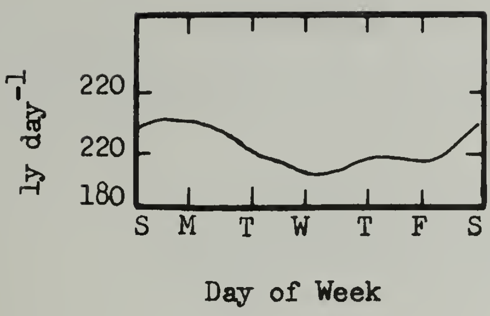

FIGURE 3. WEEKLY VARIATION IN RADIATION INTENSITY ROCHEDALE, ENGLAND (From Ashworth, 1935)

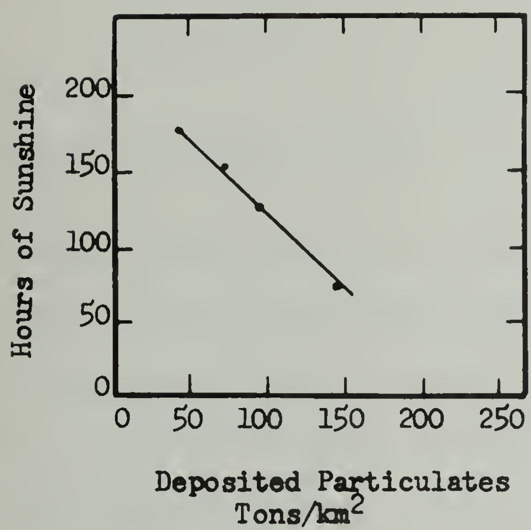

FIGURE 4. HOURS OF SUNSHINE VERSUS SETTLEABLE PARTICULATES FOR THREE WINTER MONTHS (After Brooks, 1951)

a general consequence of the "dirtiness" of the city and the city's effectiveness in melting small accumulations.

TABLE 5

SOME REPRESENTATIVE ALBEDOS[a]

Surface Type	Locality	Month	Albedo, %
Farmland	Indiana	Sept.	14-16
City	Bloomington, Ind.	Sept.	14-16
Farmland	Wisconsin	Sept.	15
Farmland	Wisconsin	Feb.	37
City	Madison, Wisc.	Sept.	16
City	Madison, Wisc.	Feb.	14

[a]From Kung, Bryson and Lenschow (1964)

Radiation losses from the city have not been investigated in any depth. Many authors have discussed the problem qualitatively suggesting that the city structure reduces the radiation loss compared to that found in the rural environs. Geiger (1965) and Sundborg (1951) argue that this concept is in error. Using Figure 5 and Table 6 it can be seen that in a street, where the rows of houses on either side are of equal height, the radiation loss from the street is less. However, the amount of decrease is highly dependent on the angles which are present.

a b. c.

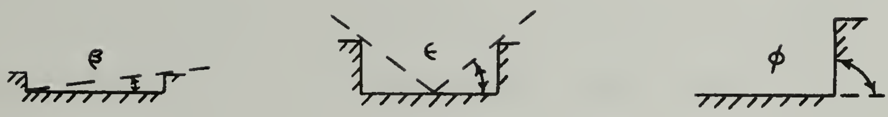

FIGURE 5. TOPOGRAPHIC FEATURES AND RADIATION LOSS

TABLE 6

EFFECTIVE OUTGOING RADIATION AS A PERCENTAGE
OF THAT FROM AN OPEN HORIZONTAL SURFACE[a]

Angle (°)[b]	0	5	10	15	20	30	45	60	90
β	100	93.0	86.2	79.7	73.7	62.2	45.2	29.6	0
ϵ	100	99.3	98.4	97.6	95.8	90.2	75.4	54.4	0
ϕ	100	--	--	--	--	--	--	--	39.6

[a]After Lausher (1934)

[b]Angles are those indicated in Figure 5

For urban residential areas the angle β (Figure 5 and Table 6) is likely to be 10° or less while ϵ is near 20°. Although the values for ϕ were developed considering no other vertical surface, and thus the radiation for 90° must be somewhat reduced, there is still a contribution. As a result, in residential areas, the radiation from

the street surface, lawn and two bordering walls is as great as the radiation from a surface visualized as an open horizontal surface at roof level (Geiger, 1965).

For commercial areas β becomes about 35° and ϵ about 55°. Although Geiger (1965) again argues that the effective radiating surface is the same as an open horizontal surface, this argument is not as easy to accept as the one above. The difference, however, is probably not enough to reduce the radiation loss more than 20 percent.

The mist and haze of urban areas may account for a considerable portion of the protection against nocturnal radiation losses which is normally attributed to the city's structural configuration.

5. Temperature

As was pointed out previously, temperature conditions and differences were among the first elements of urban climate to be investigated. As a consequence a large number of investigations have been devoted to the subject.

Various statistics and illustrations are available to verify Howard's (1818) early recognition of the urban heat island phenomenon. Landsberg's (1956) tabulation reveals that the phenomenon is general in nature and strong enough to be reflected in annual patterns.

TABLE 7

URBAN-RURAL TEMPERATURE DISPARITY[a]

Number of Cities	Population	Average Annual Temperature Excess, °C
10	1×10^6	0.72
10	$0.5 \times 10^6 - 1 \times 10^6$	0.61
10	$0.1 \times 10^6 - 0.5 \times 10^6$	0.56

[a]From Landsberg (1956)

The annual variation of the heat island is depicted graphically in Figure 6, and the diurnal pattern is shown in Figure 7. Figures 6 and 7 reveal that the maximum disparity in urban-rural temperatures is expected to be at night. The daytime effect, when it exists, appears to be small. Individual cases, of course, may vary greatly depending on the circumstances. With highly favorable conditions city temperatures 19°C higher than rural temperatures have been reported (Summers, 1965), and towns with populations as small as 20,000 have exhibited heat island effects (Duckworth and Sandberg, 1954; Hutcheon *et al.*, 1967).

Sundborg's work (1950;1951) in Uppsala, Sweden is the most comprehensive in relating the "simple" meteorological factors which affect the heat island. For Uppsala he found the following (statistical and not necessarily causal) relationships.

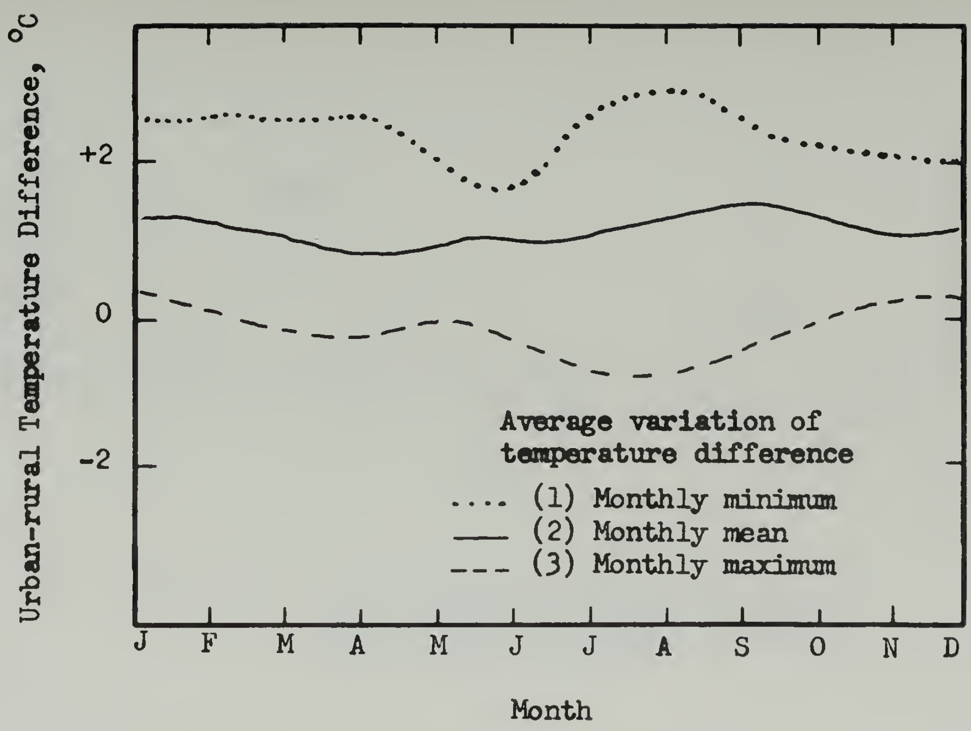

FIGURE 6. MUNICH'S ANNUAL VARIATION IN URBAN-RURAL TEMPERATURE DIFFERENCE, 1923-1926 (From Kratzer, 1956)

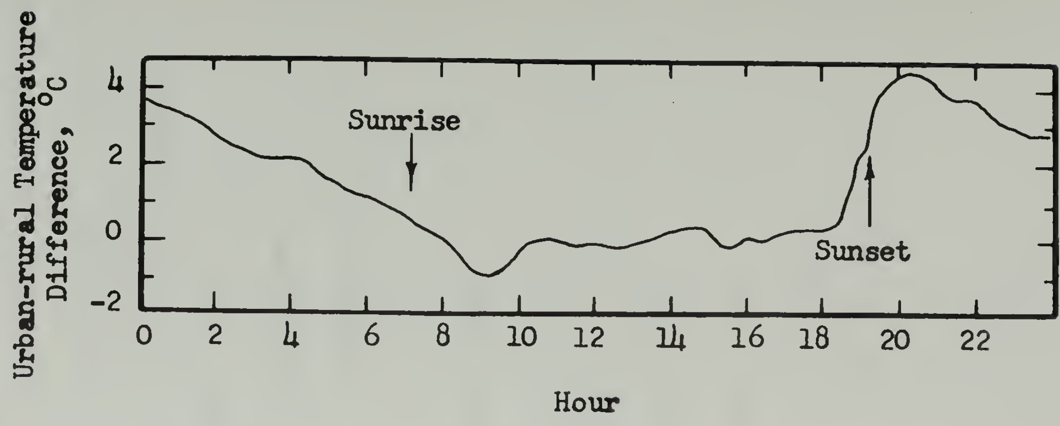

FIGURE 7. KARLSRUHE-OST DIURNAL VARIATION IN URBAN-RURAL TEMPERATURE DIFFERENCE (From Peppler, 1933)

$$D_{day} = 1.4 - 0.01 - 0.09\,\bar{u} - 0.01\,T - 0.04\,e \qquad (4)$$

$$D_{night} = 2.8 - 0.1\,N - 0.38\,\bar{u} - 0.02\,T + 0.03\,e \qquad (5)$$

where D = urban-rural temperature difference, ^{o}C

N = cloudiness, in tenths

$\bar{u}$ = wind speed, m sec^{-1}

T = temperature, ^{o}C

e = absolute humidity, mm of Hg

The coefficients of correlation between $D_{obs.}$ and $D_{cal.}$ were found to be 0.49 ± 0.05 and 0.66 ± 0.03 for day and night respectively. These equations reveal the nature of the "highly favorable" conditions mentioned above, namely that of clear, calm, cold nights. In contrast, overcast, windy, warm days yield the least heat island effect. The observations of Chandler (1960;1965) and Duckworth and Sandberg (1954) corroborate the strong role of wind speed in determining the strength of the heat island. With "surface" winds greater than 10 meters per second, the heat island was completely eliminated in London while winds of only 3 meters per second were sufficient in Palo Alto, California.

In all of the heat island studies the greatest temperature contrast has been between the built-up commercial area and the surrounding country side. In other words, the isothermal maps were essentially concentric about the commercial district being only slightly displaced and/or elongated by the prevailing wind. Although some reservation might be expressed as to topographic influence, the heat island has formed in some cases (Hutcheon, et al., 1967) in direct contrast to the expected topographic effect. (With favorable

topography one might then assume an even stronger heat island effect.)

The vertical extent of the urban heat island has been examined in only a limited manner. Fritzsche and Stange (1936) were the first to investigate temperature structure over the city. Subsequent introduction of television towers has improved the general impressions both in time as well as elevation but, unfortunately, not in space.

In general, comparison of urban and rural vertical temperature profiles (DeMarrais, 1961) has revealed that during daylight hours little difference exists while at night there is a definite contrast. With the exception of the early morning non winter hours, temperature inversions do not develop over the urban area. Instead, a weak lapse condition usually exists while the rural area develops a strong inversion. The daylight profiles show a more seasonal pattern with stronger lapse conditions existing over the city in the months October through February and in July. The reverse process occurs in August with no differentiation for the other months. As Deland and Binkowski (1966) graphically illustrate, all of these generalizations must be tempered by local circumstances. (Figure 8).

One of the most significant investigations of vertical temperature modification was that of Duckworth and Sandberg (1954). They made 32 pairs of simultaneous wiresonde soundings over urban and rural areas under conditions which were favorable to the formation of the heat island. Of the 32 soundings made over the open areas, 30 of the 32 showed an inversion. In contrast, only seven inversions between street and roof level were observed in the city, with seven

isothermal and eighteen lapse conditions observed in the other soundings. At an elevation varying between 30 and 90 meters the urban and rural profiles coincided (Figure 9) indicating the limit of the heat island effect.

D. Dispersion of Air Pollutants

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The systematic investigation of Leicester in the period 1937 to 1939 (Department of Scientific and Industrial Research, 1945) was the first large-scale, long-term effort to establish the patterns of pollution in an urban area. The qualitative results of this and subsequent investigations (for example U.S.P.H.S., 1961; Larsen, Stalker and Claydon, 1961) revealed one important feature. The point of maximum concentration of pollutants is only slightly displaced by prevailing wind from the center of maximum emissions.

For the same reasons that vertical temperature data are scarce, vertical profiles of urban pollutant concentrations are almost nonexistent. However, the few observations of McCormick and Baulch (1962) do provide some qualitative information. Their results indicate that "pollutant" depth is a function of the vertical temperature distribution. A primary pollution envelope is usually well marked by its coincidence with the depth of the unstable mixing layer (as defined by Holzworth, 1964).

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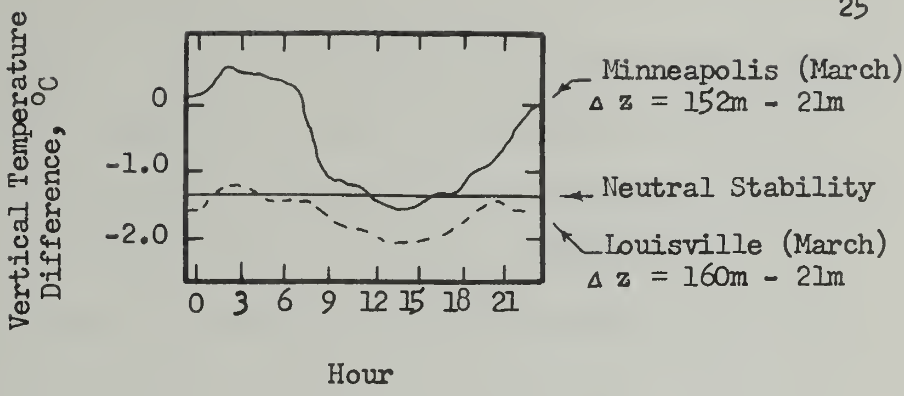

FIGURE 8. DIURNAL VARIATION OF VERTICAL TEMPERATURE DIFFERENCE (From Deland and Binkowski, 1966)

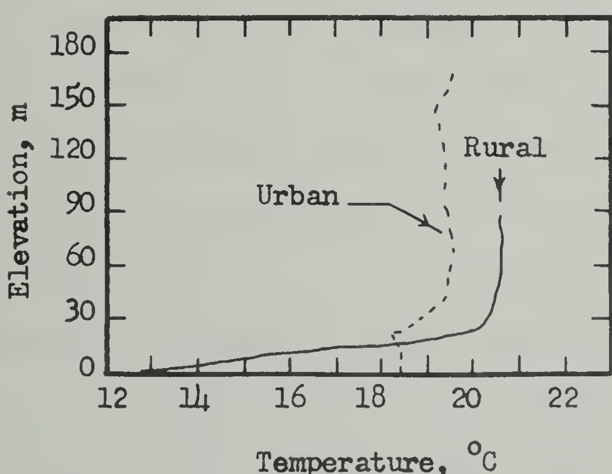

FIGURE 9. THE "CROSSOVER" OF TEMPERATURE PROFILES (From Duckworth and Sandberg, 1954)

density at ground level; and (2) "Stability Index" (no vertical temperature profiles were taken) ranks second in explaining variance but is closely related to wind speed. Similar findings have been reported by Robinson (1961) and Turner (1961) with actual stability data.

On the basis of continuity one would expect pollutant concentrations to vary inversely with the wind speed, i.e. a unit increase in wind speed results in a unit decrease in concentration. The results of the Leicester survey (Department of Scientific and Industrial Research, 1945) showed that pollutant concentration was more closely related to the inverse square root of wind speed rather than to the first power. Lucas (1958) suggested that this departure could be explained on the basis of "effective plume height" variation with wind speed. In a neutrally stable atmosphere, the rise due to velocity and buoyancy of the plume tend to increase with a decrease in wind speed, thus raising the effective stack height and correspondingly reducing ground level concentrations. The tendency for the plume to rise is essentially stifled in a stable atmosphere. Consequently, the effect of destruction of inversions by the urban heat island is to reduce ground level concentrations from sources within the city.

In contrast, Hilst and Bowne (1966) have reported some striking features of the effect of the heat island on pollutants originating upwind of the urban area. If pollutants are released from an elevated source upwind of a city with a lapse rate that is greater than isothermal, the descent to the ground is weak. When the lapse rate goes to neutral, a marked increase in ground level concentrations results. Thus, for elevated sources upwind of the city, the heat

island effect on stability is deleterious rather than beneficial.

E. Modeling Atmospheric Dispersion

The use of models to study dispersion of individual stack plumes has proven to be a reasonably satisfactory means of investigation. The early work of Sherlock and Stalker (1941) on tall stack effluents has been developed considerably in subsequent investigations (Sherlock and Lesher, 1954; Hewson, 1955; Strom and Halitsky, 1955; Strom, Hackman and Kaplin, 1957). Halitsky (1962, 1963, 1965) has extended these studies to low-level stacks while Davies and Moore (1964) and Martin (1965) have considered the specific case of nuclear reactors. All of these investigations emphasize the wealth of knowledge on dispersion than can be made available with moderate effort and expense in modeling in comparison with the pain involved in extracting only minor bits of information from prototype studies at excessive costs.

Application of modeling techniques to the study of urban dispersion patterns has been restricted by the requirements necessary to achieve similarity. Although city-wide diffusion has not been successfully treated, local diffusion from a point source in a city has been investigated (Rouse, 1951a; 1951b). The results of these tests indicated the feasibility of the technique but little has been done to expand the investigations.

Pocock (1960) and Hidy (1966; 1967) have summarized much of the experience which has been gained in the field of atmospheric simulation.

Of particular interest in considering the application of modeling techniques to urban areas are the experiences of Plate and Quaraishi (1965). Although their studies were confined to attempts to model velocity distributions inside and above crops, the complexity of the flow within and above a city might be resolved by similar techniques. If the velocity profiles inside the canopy are considered in nondimensional form, all field and laboratory data for a given crop fall into a characteristic type of curve (but not necessarily the same curve). Plate and Quaraishi (1965) recommended further experimentation to establish a correspondence between the mean velocity distribution and the turbulence field for different spacings of the model and prototype.

Much of the recent work in the field of atmospheric modeling has been devoted to problems of the boundary layer. In particular there has been a strong interest in trying to develop successful theories and techniques for modeling atmospheric turbulence and, subsequently, diffusion processes on a very refined scale (Strom, 1966).

Maynard (1966) has proposed a dimensionless modeling parameter which may have merit for a limited class of flows. The necessity of obtaining measurements, both in the model and in the prototype, of turbulent velocity components severly restricts the utility of this method.

An attempt to use curved tunnels to approximate atmospheric turbulence has been proposed (Margolis, 1967). Although the turbulence characteristics appear to behave satisfactorily, the difficulties of attaining geometric similarity have not been considered sufficiently

to make wide use of the method.

The development of theoretical considerations from arguments of similarity theory appears to be the most significant advance in atmospheric modeling. The recent reports of the application of model laws based on similarity theory from Colorado State University (Cermak, et al., 1966; Plate and Lin, 1966) and the proposals of the Cornell Aeronautical Laboratory (McVehil, et al., 1967) foretell of significant advances in the modeling of atmospheric phenomena.

CHAPTER III

SCOPE OF INVESTIGATION

The mathematical dispersion models for predicting urban air pollution distribution (for example Clarke, 1964; Miller and Holzworth, 1966; Pooler, 1961; Turner, 1964) have as a foundation the Gaussian type of formula:

$$X_{(x,y,z)} = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp \left[- \frac{1}{2} \left(\frac{y^2}{\sigma_y^2} - \frac{z^2}{\sigma_z^2} \right) \right] \quad (6)$$

where $X_{(x,y,z)}$ = Concentration of gaseous pollutant at coordinate (x, y, z), g m^{-3}

Q = Emission rate of gaseous pollutant, g sec^{-1}

σ_y = Horizontal variance of pollutant concentration, m

σ_z = Vertical variance of pollutant concentration, m

For the dispersion models, calculations of $X_{(x,y,z)} / Q$ are usually the main objective. Meteorologically, estimates of $\bar{u}$, σ_y and σ_z are required. Although $\bar{u}$ is implied to be the average wind speed through the layer of interest, it is usually measured at some arbitrary height. Use of either of these assumptions is contrary to the established fact of rapid change of the wind speed with height and results in compensation in the variances (Singer and Smith, 1966). The variances σ_y and σ_z are expressed semi-theoretically in terms of distance from the source and parameters related to the turbulence of the atmosphere. Although they may be experimentally determined

(Pasquill, 1962), they are usually inferred from nomographs related to atmospheric stability.

The supposition, under which this investigation was designed, was that the distribution of pollutants in an urban area could be more accurately described if more detailed stability information was available as suggested by Turner (1964). Because of the inherent economic limitations in securing this information in full scale studies, the methods of modeling were considered. The hope was to realize Pocock's (1960) suggestion that for limited meteorological conditions one might be able to combine dispersion theory with model studies.

Performing experiments to produce a model atmosphere in a wind tunnel both removes and introduces difficulties. The primary advantages of a wind tunnel are the absence of restrictions imposed by existing weather and the ability to remove irregularities of surface roughness.

On the other hand, there exist boundary layers on the ceiling and walls of the wind tunnel which certainly do not exist in the atmosphere. Thus, the walls severly restrict the model size. This in turn often results in scale effects which unduly distort the behavior of the model (Langhaar, 1951). In addition, all attempts to produce a spectrum of turbulence which coincides with that found in the atmosphere have been somewhat deficient (Lloyd, 1967; Owen and Zienkiewicz, 1957; Strom and Kaplin, 1966; Weiss, 1959).

Because of the lack of suitable wind tunnel facilities and the inherent disadvantages of wind tunnel modeling, it was decided that

a model constructed in the ambient atmosphere would yield satisfactory behavior provided that:

1. The meteorological conditions were properly chosen.

2. A hypothesized naturally occurring similitude did indeed exist (Batchelor, 1950; 1953; Cermak, 1963; Hay and Pasquill, 1959; Kolmogoroff, 1941, Lettau, 1957; Monin and Obukhov, 1954; Obukhov, 1948; 1959; Taylor, 1960).

As was mentioned in the literature review, atmospheric stability (measured by vertical temperature profiles) over the urban area differs little from that found in the rural area during daylight hours. On clear, calm nights, however, the urban heat island often significantly alters the temperature profile. Because it has been this type of variation that has reduced the effectiveness of the dispersion formulae, these studies were restricted to those meteorological conditions which have been found highly conducive to the formation of the urban heat island (i.e. clear, calm nights).

The general purpose of this investigative effort was, then, to model the effect of the urban heat island on stability as measured by vertical temperature profiles.

The specific objectives included:

1. Determination of a scale factor or factors which would result in similitude of stability.

2. Validation of the scale factor with independent profiles measured under the same conditions.

3. Validation of a model law developed from hypothesized atmospheric similitude arguments.

4. Examination of several geometric lengths in order to determine a characteristic length.

The philosophy used in approaching this problem is best summarized in a recent report and research proposal from the Argonne National Laboratory (1967):

> "In designing a scale model experiment, the objective is to produce, at a reduced dimensional scale, the physical phenomena of the full-scale counterpart, such that there is a quantitative relationship between the two. For reasons of simplicity, it is ordinarily desirable to preserve geometric similarity between model and prototype. Because of conflicting requirements, compromises may be made in departing from geometric similarity to compensate for features which do not scale as desired. This yields a distorted model. An example of this technique, in which the vertical dimension has been changed in relation to the horizontal, may be found in experiments dealing with models of rivers and water waves in which the surface tension does not scale in the same way as do surface waves. If the measurements obtained in the modeling facility can be interpreted to determine what happens in the atmosphere, then success has been achieved. In effect, one calibrates the modeling facility with the atmosphere and then applies the necessary correction factors to the model experiments. After extensive experience has been gained, this technique may be applied to obtain valid information about the atmosphere from model experiments."*

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*Argonne National Laboratory (1967) Research Proposal - modeling small scale atmospheric motions micrometeological modeling facility, p. 25.

CHAPTER IV

THEORETICAL CONCEPTS

A. Introduction

The development and selection of the proper modeling criteria are obviously of major importance to the design and accuracy of scale model experiments and experimental equipment. Therefore, the first and major portion of the following discussion is devoted to the development of modeling criteria.

Another smaller portion of this chapter is devoted to the presentation of a general representation of the energy balance at the earth-atmosphere boundary. This forms the basis for later discussions regarding the experimental method as well as forming the physical basis for the heat island.

B. Similarity Considerations

The general concept of similarity may be expressed in terms of two abstract scalar functions $f(x, y, z, t)$ and $f'(x', y', z', t')$.

> "The function f' is similar to f, provided that the ratio f'/f is a constant when the functions are evaluated for homologous points and homologous times."*

The symbol K_f is used to designate the constant ratio and is termed a scale factor.

If one considers the equation of motion of the prototype and the equation of motion of the model as f and f' respectively, it

*Langhaar, H. L. (1951) Dimensional Analysis and Theory of Models, J. Wiley and Sons, New York, p. 68.

can be shown that complete dynamic similarity of flows can be achieved if the following conditions are met:

$$\frac{K_q}{K_\Omega K_L} = 1; \quad \frac{K_q^2 K_\rho}{K_L K_{\Delta\rho} K_g} = 1; \quad \frac{K_q}{K_L K_\nu} = 1 .$$

This is equivalent to establishing equal values of the Rossby number, Froude number and Reynolds number respectively in the model and prototype.

C. Modeling Criteria

The Rossby number is defined by the following equation:

$$Ro = \frac{U}{L\,\Omega} \tag{7}$$

where U = characteristic velocity, m sec^{-1}

L = characteristic length, m

Ω = angular velocity, sec^{-1}

When this ratio is large, rotational effects on the flow system are small compared to the effects of nonuniformity of the flow field. If the prototype length is less than 150 km, large differences between the prototype and model Rossby number do not produce large differences in flow patterns. This is true for turbulent flow as well as laminar flow (Cermak, et al., 1966). Therefore, in the case of modeling of an urban complex, it is not necessary to achieve equivalence of Rossby numbers and this requirement may be relaxed.

The Reynolds number is defined by the following equation:

$$Re = \frac{U\,L}{\nu} \tag{8}$$

where ν = kinematic viscosity, $m^2\ sec^{-1}$

The Reynolds number imposes a strong limitation on model similitude for any laminar prototype flows. This is because the model Reynolds number will be approximately 10^{-3} to 10^{-4} times that of the prototype for conventional geometries and wind speeds. The case for turbulent flow, however, offers greater possibilities for Reynolds number equivalence.

If one considers the action of turbulent atmospheric eddy viscosity as analogous to viscosity in small scale laminar flow, then the viscosity can be enlarged by the Boussinesq number (Lettau, 1957).

$$Bo = \frac{\tau}{\mu \frac{\partial u}{\partial z}} \tag{9}$$

where τ = fluid shear, $kg\ m^{-1}\ sec^{-2}$

μ = absolute viscosity, $kg\ m^{-1}\ sec^{-1}$

Using the definition of eddy viscosity

$$K_M^* = \frac{\tau}{\rho \frac{\partial u}{\partial z}} \tag{10}$$

where ρ = density, $kg\ m^{-3}$

it can easily be shown that

$$Bo = \frac{K_m^*}{\nu} \tag{11}$$

and that the turbulent Reynolds number then takes the form

$$(Re)_t = \frac{U\ L}{K_M^*} \tag{12}$$

This means that for turbulent flow the Reynolds number is 10^{-3} times that of laminar flow. This opens the possibility of achieving similarity of the gross mean characteristics of turbulent flows over topographical features by laminar flow experiments (Cermak and Peterka, 1966).

When the flow is over sharp-edged geometry the mean flow patterns are relatively independent of Reynolds number if a critical value of 11,000 is exceeded (Golden, 1961).

Since the urban complex falls into either the turbulent Reynolds number regime or the one of sharp edged geometry, the Reynolds number does not appear to impose stringent requirements on the modeling of gross atmospheric features over the city.

The Froude number may be defined in the following manner:

$$Fr^2 = \frac{\frac{U^2}{L}}{\frac{\Delta\rho}{\rho}\ g} \tag{13}$$

In meteorological applications with relatively small vertical differences, the specific weight differences arise primarily from temperature differences. In this case $-\Delta T/T$ may be substituted for $\Delta\rho/\rho$.

Thus, the Froude number may be rewritten:

$$Fr^2 = -\frac{\frac{U^2}{L}}{\frac{\Delta T}{T}\, g} = -\frac{\frac{U^2}{L^2}}{\frac{g}{T}\left(\frac{\Delta T}{L}\right)} \qquad (14)$$

The inverse form of this parameter often occurs in the meteorological literature as the Richardson number:

$$Ri = \frac{g \frac{\Delta T}{\Delta z}}{T\left(\frac{\Delta U}{\Delta z}\right)^2} \qquad (15)$$

Batchelor (1953) has shown, _mutatis mutandis_, that, near a rough boundary in a thermally stratified fluid (to a first approximation) the Richardson number is the "sole" parameter governing dynamical similarity.

Therefore, for simulation of the atmosphere over a city, equivalence of Froude numbers (Richardson numbers) must be achieved.

In its original definition by Richardson (1920), the Richardson number denoted a local energy parameter signifying the influence of buoyancy in enhancing or damping turbulent motion in a thermally stratified fluid. The original definition was given in the flux form:

$$Rf = \frac{g\, H}{C_p T\, \tau\, \frac{\partial u}{\partial z}} \qquad (16)$$

where H = sensible heat flux, ly min^{-1}

C_p = specific heat at constant pressure, g-cal g^{-1} $^{o}K^{-1}$

T = absolute temperature, ^{o}K

The gradient form of the Richardson number given in equation (15) is related to the flux form in the following manner:

$$Ri = \frac{K_M^*}{K_H^*} Rf \tag{17}$$

Often the assumption is made that K_M^* / K_H^* = constant; however, recent measurements indicate that this ratio depends on the distance from the ground at which measurements are taken (Cermak, et al., 1966). This height dependency means that a different type of stability may be found for different distances from the boundary.

Since elevations are to be scaled in performing model experiments, it is necessary to define a stability parameter which is independent of elevation. In other words, the Richardson number must be chosen to represent the gross features of the fluid motion and temperature field so that the same value may be achieved in both the model and the prototype. As was mentioned above, the gradient Richardson number is a function of the distance from the wall, and thus, cannot be used to describe the flow field everywhere, and, therefore, cannot be used as the modeling criterion. The flux form of the Richardson number (or some parameter directly related to it) must be used as the modeling criterion.

Monin and Obukhov (1954) applied the methods of the theory

of similitude to develop three parameters which they considered definitive of the turbulence characteristics in the ground layer of the atmosphere. The three parameters were: g/T; U and H/C_p . By dimensional analysis they combined these terms to form a "scale length of turbulence,"

$$L_* = \frac{U^3 C_p \rho T}{g H} . \tag{18}$$

In the original discussion Monin and Obukhov assumed that the friction velocity, u_*, was the characteristic velocity. In addition they introduced a negative sign and von Karman's constant, k, "for the sake of convenience."* The final result is then the more familiar form of the Monin-Obukhov scale length,

$$L_* = - \frac{(u_*)^3 C_p \rho T}{k g H} . \tag{19}$$

This form is very closely related to the flux form of the Richardson number (equation 16). If one recalls the definition of the friction velocity,

$$u_*^2 = \frac{\tau}{\rho} , \tag{20}$$

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*Monin, A. S. and A. M. Obukhov (1954), "Basic Laws of Turbulent Mixing in the Ground Layer," Akademiic Nauk USSR Geofizicheskii Inst., Trudy, 24, p. 173.

then the flux form of the Richardson number may be rewritten:

$$R_f = \frac{g\,H}{C_p T \, u_*^2 \, \frac{\partial u}{\partial z}} \quad . \tag{21}$$

If one now non-dimensionalized the Monin-Obukhov scale length by forming the ratio z/L_*, then

$$\frac{z}{L_*} = - \frac{z\,k\,g\,H}{C_p \, T \, \rho \, (u_*)^3} \quad . \tag{22}$$

With the differential form of the "logarithmic wind law,"

$$\frac{u}{z} = \frac{u_*}{kz} \quad , \tag{23}$$

equation (22) may be rewritten:

$$\frac{z}{L_*} = - \frac{g\,H}{C_p \, T \, \rho \, u_*^2 \, \frac{\partial u}{\partial z}} \tag{24}$$

and with equation (21)

$$- \frac{z}{L_*} = R_f \tag{25}$$

which confirms the direct relationship between the flux Richardson number and the "convenient" choice of k and u_* as characteristic parameters.

The above exercise provides a desirable and related alternative to the Richardson number for use as a modeling parameter, namely the right-hand side of the equation (22).

D. Autogenous Atmospheric Simulation

In choosing the real atmosphere as the medium in which to perform model studies, one is confronted with the necessity of depending on the existence of naturally occurring similitude. The scale length of turbulence, L_*, was developed by Monin and Obukhov (1954) on the fundamental assumption that "the statistical characteristics for relative movements in a stream are invarient with respect to transformations of similitude: $x' = kx$; $y' = ky$, $z' = kz$ and $t' = kt$."* Batchelor (1957), Gifford (1962), Cermak (1963) and Panofsky and Prasad (1965) compared diffusion experiments over a wide range of scales (from wind tunnels to full scale) and confirmed the assumption that the turbulence characteristics are determined by the shear velocity, u_*, and the Monin-Obukhov scale length, L_*.

The existence of a similarity, in the Lagrangian sense, in the turbulent motions of shear flow, which is governed by the same criteria as those which are required for modeling of phenomena in the wind tunnel, makes it possible to carry out atmospheric modeling experiments from the general arguments of modeling criteria given above.

Although the arguments for naturally occurring similitude do not explicitly deal with the flux Richardson number, Rf, its close

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*Monin and Obukhov (1954) "Basic Laws of Turbulent Mixing in the Ground Layer of the Atmosphere," Akad. Nauk USSR, Geof. Inst. Trudy, 24, p. 4.

relationship to the Monin-Obukhov scale length, L_*, implicitly requires that it also be considered as a possible scaling parameter. The recent success in using L_* for modeling work at Colorado State University (Plate and Lin, 1966 and Cermak, 1967) leads to the conclusion that the dimensionless ratio z/L_* is "the" scaling parameter.

For the purpose of discussion the modeling parameter is rewritten in expanded form:

$$\frac{L\ k\ g\ H}{C_p\ T\ \rho\ (u_*)^3} \quad . \tag{26}$$

This ratio assumes the significance of a scaling parameter only if there exists a possibility to define uniquely a characteristic temperature, T; heat flux, H; friction velocity, u_*; and length L.

In a given layer of the atmosphere the variations of temperature will be relatively small compared to the absolute value. Thus, the characteristic temperature can be defined by taking the average temperature over the layer (Plate and Lin, 1966).

In general, changes of heat flux, H, with small downwind distances are generally negligible in the atmosphere which again makes it possible to use an average value for the purpose of characterization. However, the imposition of a heat source, such as the urban heat island, presents a problem in selection of a suitable scaling heat flux because of the presence of a developing thermal boundary layer.

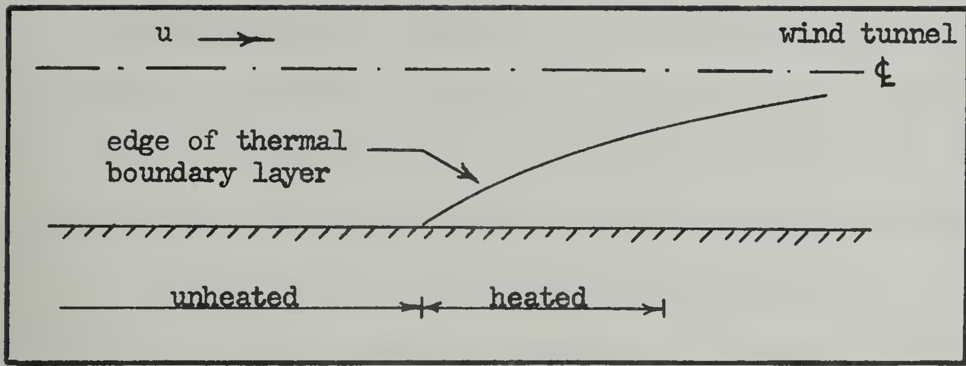

FIGURE 10. SCHEMATIC DEVELOPING THERMAL BOUNDARY LAYER

Plate and Lin (1966) derived a formulation for L_* which depends on a power-law description of developing temperature and velocity profiles. This allows L_* to be described in terms of the gross parameters of wind tunnel conditions which differ from atmospheric conditions because of the imposition of a heat source. In the case where both the model and prototype impose a heat source, a reasonable course of action is to select the measurement of heat flux at corresponding downwind distances in the prototype and model.

The classical definition of the friction velocity, u_*, and the "normal" methods for measuring it depend heavily on the existence of the classical logarithmic wind profile. In general, this condition is only infrequently achieved and other estimating techniques are employed. For experimental purposes one can use a form analgous to the generalized equation for the velocity profile for turbulent flow in wholly rough pipes. That is, the wind speed measured at an elevation y over a roughness z_o is a proportion of the friction velocity

and thus characterizes the velocity.

The characteristic length, L, is a dimension which relates the dependence of atmospheric phenomena to the geometry. Jensen (1958) and Inoue (1959) were able to show that the ratios h/z_o and h/L_* must both be equal in the model and in the prototype for similarity of a diffusion field. The ratio h/z_o represents the ratio object height, h, to the roughness length, z_o. This means that the characteristic length is directly related to the roughness length. The model geometry should then be a function of the roughness parameter, z_o. Unfortunately, the theoretical foundation for determining z_o is poor and values are difficult to determine in both the atmosphere and the laboratory. Hence another method of determining the reference length is desirable. A satisfactory alternative, for experimental purposes, would be the determination of the ratio $(z)_m$ / $(z)_p$.

The model law for autogenous atmospheric simulation follows directly from the dimensionless parameter. By definition a model law requires that

$$\left(\frac{L\ g\ H\ k}{U^3\ T\ C_p \rho}\right)_{\text{prototype}} = \left(\frac{L\ g\ H\ k}{U^3\ T\ C_p \rho}\right)_{\text{model}} . \qquad (27)$$

Equation (27) may be simplified if the model and prototype experiments are conducted on the same fluid under the same gravitational field. In this case $g_m = g_p$; $k_m = k_p$; $(C_p)_p = (C_p)_m$. Further simplification will result if one recognizes that the model and prototype temperatures and hence fluid densities will not be

appreciably different from one another. Thus equation (27) may be rewritten in the following form:

$$\left(\frac{L\,H}{U^3}\right)_{\text{prototype}} = \left(\frac{L\,H}{U^3}\right)_{\text{model}} \quad . \tag{28}$$

From the concept of similarity the model law then becomes:

$$\frac{Lm}{Lp} \times \frac{Hm}{Hp} \times \frac{(U_p)^3}{(U_m)^3} = 1 \tag{29}$$

or

$$K_L \times K_H \times \frac{1}{(K_U)^3} = 1 \quad . \tag{30}$$

Turbulence in the atmosphere may be considered to be basically either convective or mechanical in origin. The former is related to lapse rate, or more accurately to potential temperature lapse rate, while the latter is related to wind speed. Although the potential temperature is defined as the temperature a parcel of dry air would have if brought adiabatically from its initial state to a standard sea-level pressure of 1000 mb, it may be approximated in the surface boundary layer by the following expression:

$$\theta = T + \Gamma z \tag{31}$$

where θ = potential temperature, ^{o}K

Γ = dry adiabatic lapse rate, -10^{-2} $^{o}C\ m^{-1}$

Strom and Kaplin (1960) have shown that, if the density profile (potential temperature profile) is one of the independent variables of the modeling experiment, then

$$\left(\frac{dT}{dz} + \Gamma\right)_{\text{prototype}} = \frac{Lm}{Lp} \left(\frac{dT}{dz} + \Gamma\right)_{\text{model}} . \tag{32}$$

This requirement is, of course, in addition to the other established modeling criteria and must be compatible with them. The model law for atmospheric simulation also requires that

$$K_L = \frac{K_u^{\,3}}{K_H} . \tag{33}$$

For the simulation of the effect of the heat island on stability, equation (32) must be validated. If one replaces the derivatives with increments ΔT and Δz, then equation (32) takes the form

$$\left(\frac{\Delta T}{\Delta z} + \Gamma\right)_p = K_L \left(\frac{\Delta T}{\Delta z} + \Gamma\right)_m . \tag{34}$$

Now let us assume that the potential temperature profiles are measured over homologous lengths at homologous points in the model and prototype. Then K_L assumes the value $\Delta z_m/\Delta z_p$ and equation (34) may be rewritten in the following manner:

$$z_p \left(\frac{\Delta T}{\Delta z} + \Gamma\right)_p = \Delta z_m \left(\frac{\Delta T}{\Delta z} + \Gamma\right)_m \tag{35}$$

which expands to

$$T_p + \Delta z_p \Gamma = T_m + \Delta z_m \Gamma . \tag{36}$$

If a model T_m can be found which is equal to the prototype T_p, then the equivalent model length is determined, and the scale factor is given by equation (37):

$$K_L = \frac{Z_m}{Z_p} \tag{37}$$

Independent temperature profiles at another homologous point can be used to test the homology of the scale factor.

With a valid geometric scale factor, K_L, a test of the model law (equation 27) may be made by considering equation (33), repeated here for the purpose of discussion.

$$K_L = \frac{K_u^3}{K_H} \tag{33}$$

If the model law is valid, then the right-hand side of equation (33) must yield the same value of K_L as determined from the fitted temperature profiles. In other words, because the scale geometry is fixed by the physical characteristics of the prototype and the model constructed to represent it, only that combination of variables (U and H) which yields the exact K_L will yield similitude of potential temperature profiles. Thus, scaling of the profiles cannot be approached by randomly applying the right-hand side of equation (33). Likewise, random application of the left-hand side of equation (33) to model

temperature profiles will not yield simulation unless the variables on the right-hand side give an equivalent value of K_L.

This technique does not, of course, exclude the possibility that other modeling criteria might be equally as acceptable as z/L_*.

E. Energy Balance at the Earth-Atmosphere Boundary

1. The energy balance equation

For the purpose of discussion it is assumed that the earth's surface is extensive and entirely horizontal. The boundary between the atmosphere and the earth is then a plane. Through this plane a heat exchange process occurs which may be represented by the energy balance equation:

$$R_n = G + E - Q + H \tag{38}$$

where R_n = net radiation (+ downward), ly $\min^{-1}$

G = heat flow into surface (+), ly $\min^{-1}$

E = contribution of latent heat of evaporation (+) or condensation (-), ly $\min^{-1}$

Q = sensible heat contribution from human activity (+ downward), ly $\min^{-1}$

H = turbulent flux of sensible heat (+ upward), ly $\min^{-1}$

2. Radiation components

The net radiation (R_n) passing through the imaginary plane is made up of five components during the daylight hours. These components are related in the following manner:

$$R_N = R_s + R_D + R_L - \sigma T^4 \epsilon - \quad (R_s + R_d) \tag{39}$$

where R_n = net radiation, ly min^{-1}

R_s = solar radiation, ly min^{-1}

R_d = diffuse radiation, ly min^{-1}

R_l = long wave atmospheric counter radiation, ly min^{-1}

σT^4 = black body radiation, ly min^{-1}

ϵ = emissivity

σ = Stephan-Boltzman constant

T = absolute temperature of surface, ^oK

$\alpha (R_s + R_d)$ = reflected radiation, ly min^{-1}

α = albedo

At night equation (39) reduces to

$$R_N = R_L - \sigma T^4 \epsilon \tag{40}$$

3. Heat flow into surface

In the simplest terms, the capacity of a surface to absorb and give up heat is dependent on the thermal conductivity of the surface material and the temperature gradient through the material:

$$G = - \lambda \frac{\partial T}{\partial z} \tag{41}$$

where G = heat flow into surface, ly min^{-1}

λ = thermal conductivity, g-cal cm min^{-1} cm^{-2} $^{o}C^{-1}$

$\frac{\partial T}{\partial z}$ = temperature gradient into material (measuring depth from the surface), ^{o}C cm^{-1}

4. Contribution of latent heat

The contribution of latent heat is related to water loss by equation (47):

$$E = 600\ V \tag{42}$$

where E = contribution of latent heat, ly min^{-1}

600 = latent heat of evaporation, cal g^{-1}

V = rate of evaporation, g m^{-2} sec^{-1}

5. Heat contribution from human activity

The existence of urban activity has often been suggested as a significant contribution to the heat island phenomenon. The components of heat contribution are summarized by equation (43):

$$Q = s + i + a + p + m \tag{43}$$

where Q = sensible heat contribution from human activity

s = space heating

i = industrial process heating

a = automotive heat production

p = power plant heat losses

m = animal metabolic activity

6. Turbulent heat flux

The vertical transfer of heat is the result of the turbulent motion of the medium. Using the classical Prandtl mixing length principle, it can be shown that the upward turbulent transport of heat may be expressed in the following form:

$$H = - K_H C_p \rho \frac{\partial \theta}{\partial z} \tag{44}$$

When the motion, or that part of the motion which carries the heat, is itself set up by bouyancy, the turbulent heat flux may be expressed in an alternative and more convenient form (Prandtl, 1932; Priestley, 1954; 1959):

$$H = - b \; C_p \rho \left(\frac{g}{T}\right)^{1/2} L^2 \left(\frac{\partial T}{\partial z} + \Gamma\right)^{3/2} \tag{45}$$

Dyer (1965) found the constant, b, to be 1.32.

CHAPTER V

MATERIALS AND METHODS

A. The Prototype

1. Selection of prototype

The basic question in assessing the utility of modeling is that of how closely it is possible to duplicate, on a reduced scale, the characteristics of the full scale prototype. This question can be answered only by extensive comparisons of model and prototype observations.

The primary requirement of the prototype was that simultaneous temperature profiles at more than one location be available. This requirement was necessitated by the second objective, namely to validate a "calibrated" scale factor by applying it to an independent temperature profile under equivalent conditions.

It was also required that the prototype lie on reasonably uniform terrain and that it be isolated. These requirements were made in heed to Sir Geoffrey's admonition:

> "The best way to test one's theoretical ideas is to apply them to some case for which the geometry is so simple that one can make quantitative predictions based on those ideas and at the same time can make experiments necessary for comparison with theory."*

Because the scope of this work was concerned with the urban heat island, it was also required that the prototype data cover

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*Taylor, G. I. (1961), "Fire Under the Influence of Natural Convection" in _Int. Symposium on the Use of Models in Fire Research_, National Academy of Science, Pub. No. 786, p. 10.

recognizable heat island situations.

The only existing data which satisfied the primary requirement was that available from Fort Wayne, Indiana (Hilst and Bowne, 1966). It was fortunate that this investigation also was concerned with the effect of the heat island without topographic effects and, therefore, satisfied the other requirements for the prototype. In addition, Fort Wayne also had the advantages of being of reasonable size (approximately 10 km by 11 km) and having a well defined urban-rural boundary.

2. Site description

The city of Fort Wayne, Indiana is located in flat farm land in the northeastern portion of the state. The 1966 Fort Wayne population estimate was 179,369 (Traylor, 1967). The terrain is flat, and according to the U. S. Geological Survey topographic maps, the maximum relief within a 50 km radius is less than 60 meters. The major topographic features of the area are the St. Joseph and St. Mary's Rivers which meet near the center of town to form the Maumee River. The river valley is very shallow and only slightly effects the topography of the city.

The land surrounding the city is used for agriculture and is generally cleared of trees except along the roads and river banks.

3. Meteorological network

Meteorological information was recorded at ten surface and two tower locations. In addition, wiresondes and pibals were taken at two sites and a radiosonde ascent was made for each test period.

The surface stations were equipped with wind sensors at 9.1 m and temperature sensors at 1.5 m. In addition, four surface stations were provided with vector vanes for three-dimensional resolution of the wind velocity.

The two towers were also instrumented with wind and temperature sensors. The WANE-TV tower, located in essentially rural environs, (Figure 11) had wind and temperature sensors at levels of 12.2, 30.5, 61, 91 and 213 m above ground level. The General Telephone (GT) tower, which was located in the business district, had wind and temperature sensors at levels of 15.2, 30.5, 38.2, 45.6 and 53.5 m (Bowne, 1967).

One of the two wiresonde sites employed was located near the GT tower. At the suggestion of Hilst (1967), data from these wiresondes were used to extrapolate the vertical temperature soundings from the GT tower. The second wiresonde site was located in rural environs (Figure 11).

B. The Model Site

The uniform terrain of central Illinois provides excellent conditions for the type of model study envisioned in this research.

The major requirements used in selection of the model site were: (1) land availability; (2) absence of vertical obstructions (buildings, fences, crops, etc.); (3) availability of power.

Because of the intensive agricultural program in the central Illinois area, very few areas are at the same time free of vertical obstructions and uncultivated. However, a portion of a 40 acre plot

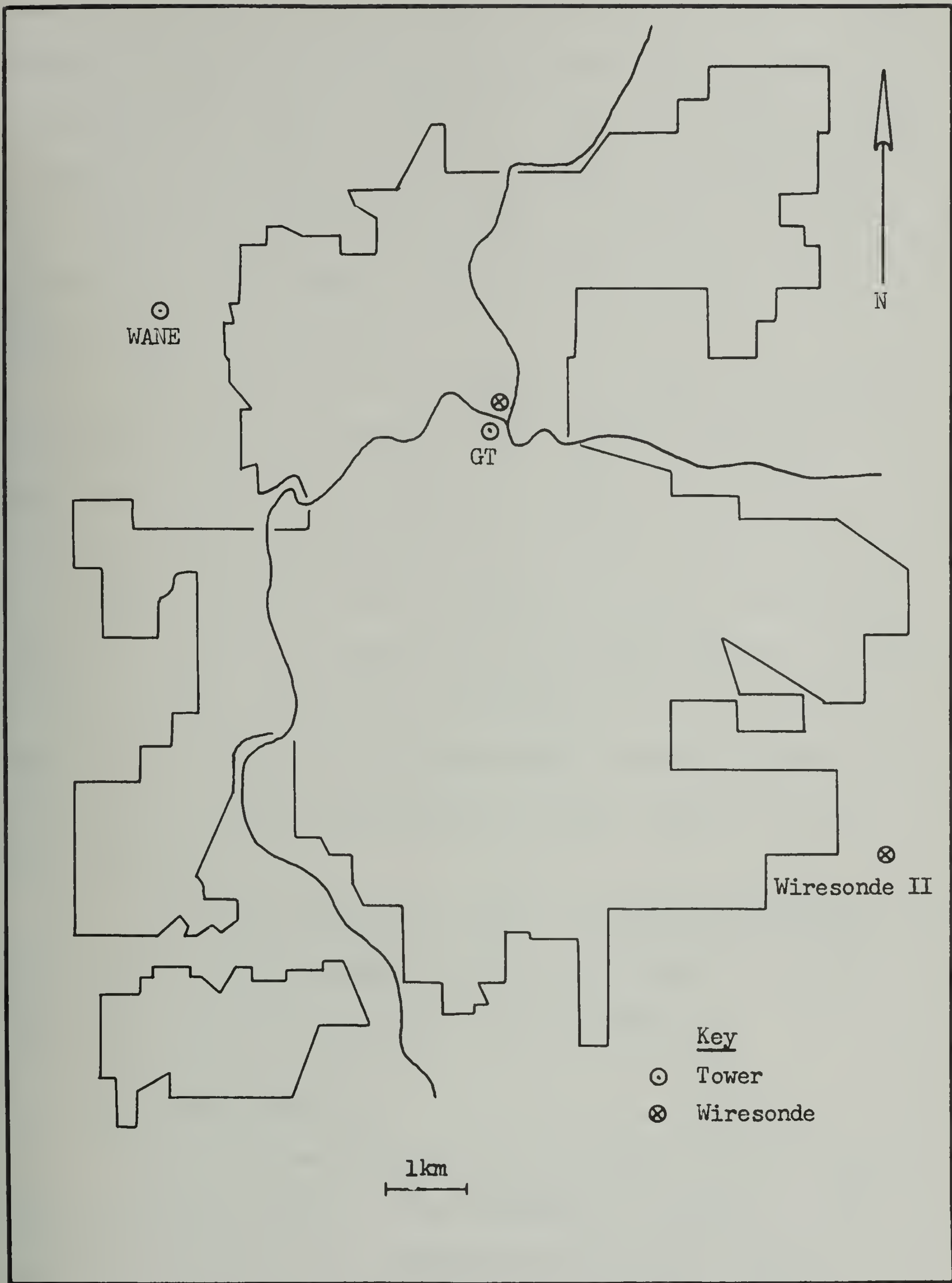

FIGURE 11. DATA SAMPLING SITES: FORT WAYNE, INDIANA

operated by the Electrical Engineering Research Laboratory (EERL) of the University of Illinois was made available for the purpose of this research. This area was graded, plowed, disced, raked and seeded (with grass) according to the requirements of the EERL. The careful preparation of this former corn field resulted in a uniform site on which to construct the model.

The exact location of the model was selected with reference to existing vertical obstructions. Since the major obstruction was chain link fence (Figure 12), the work of Nägeli (1953) on thin screens was used as a guideline in the placement of the model. It is illustrated in Figure 13 that at a downwind distance of approximately 30 times the height of a fence the flow field has essentially returned to that existing in the open. The model was located at a distance equal to 45.9 multiples of the fence height from the chain link fence. The vacant building was approximately 36 height multiples from the model (Figure 12).

The EERL had obtained a surface mounted 25 kw transformer at the trailer for their research. The load requirements of the EERL left approximately 10 kw of power for this research.

C. Orientation of the Model

All of the data taken in Fort Wayne was limited to periods when the wind was from the west to northwest. In order to achieve homology in the model, this restriction also had to be applied to data periods for the experimental program. In order to obtain as

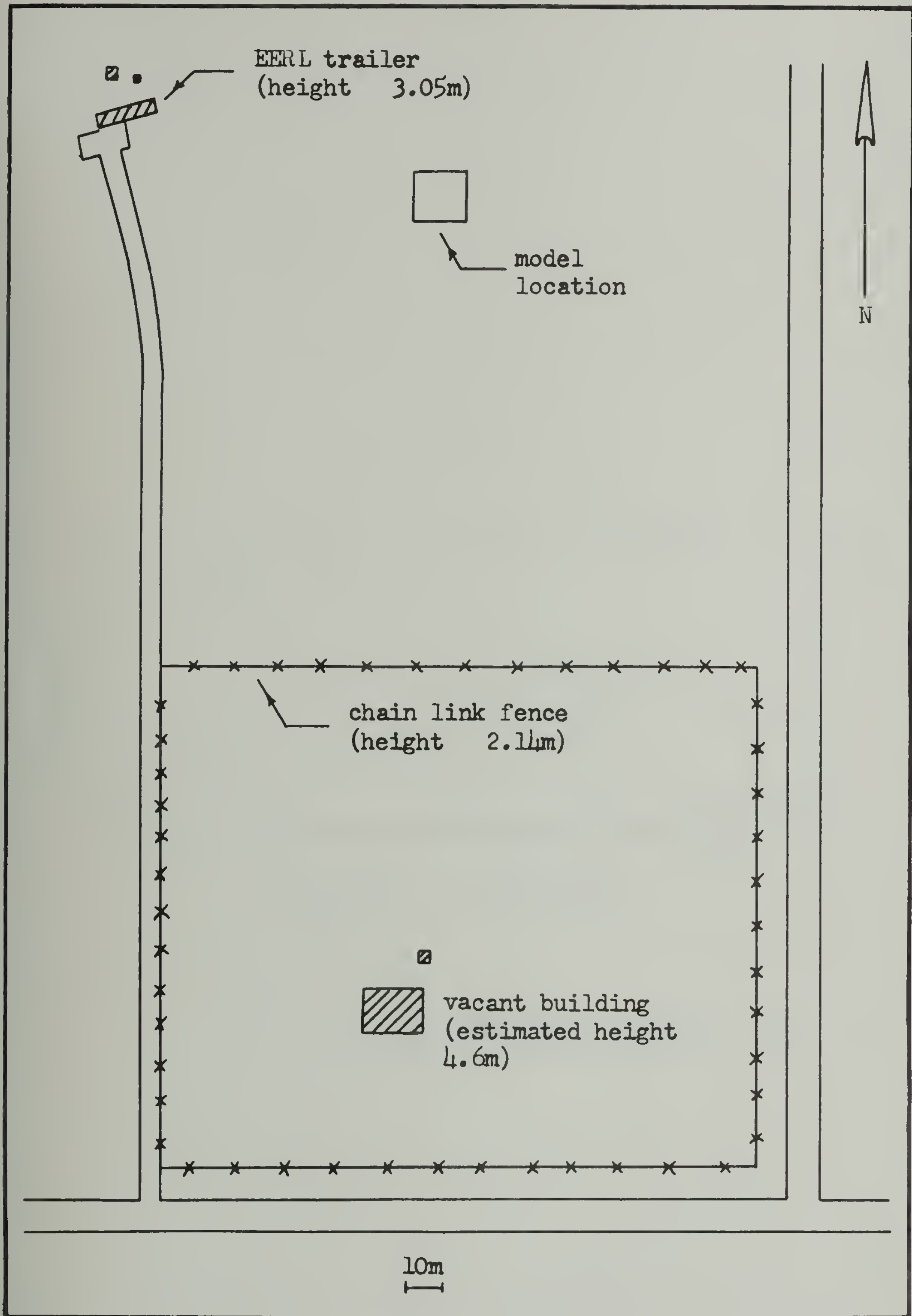

FIGURE 12. MODEL SITE: THOMASBORO, ILLINOIS

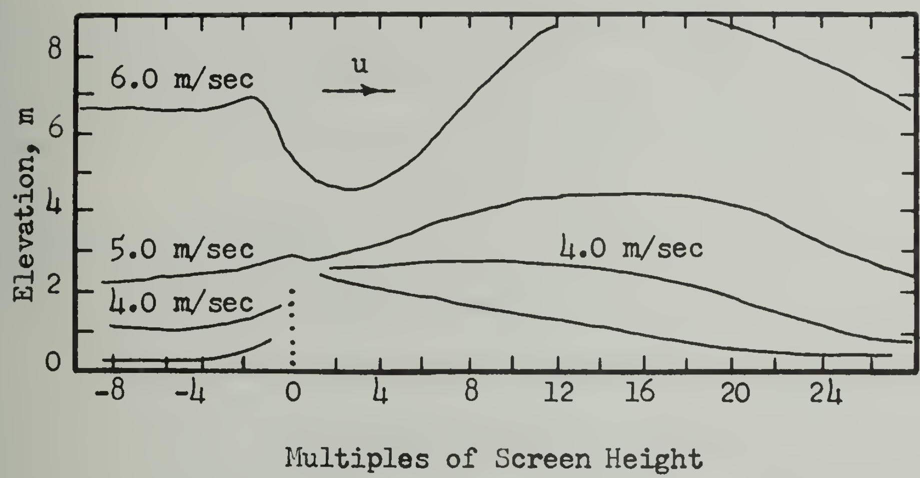

FIGURE 13. WIND FIELD AROUND A THIN REED SCREEN (From Nägeli, 1953)

many data periods as possible, the necessity of reorienting the model was considered.

In addition to the restrictions of homology, the restrictions of the model law were considered in analyzing the possibility of reorienting; the model law implies that a model constructed at a reduced scale, L, must be operated under correspondingly reduced wind speeds.

From an analysis of the predominant directions of low speed winds in the central Illinois area (Figure 14), it was decided to rotate the model counterclockwise 90° from the homologous orientation. Thus, north in the model plot was in actuality facing west.

D. Design of the Model

1. Design of heating system

In order to obtain some flexibility in the model (and hopefully some control in the variation of the heat flux, H) a heating system was designed to augment the natural radiational heating of the model heat island.

Electric soil heating elements were considered as the most practical method of supplying heat. With a horizontal scale of 1:1000 and an available power supply of 10 kw, a maximum heat output of 0.1 kw m^{-2} could be realized. This value is essentially equivalent to that found by Summers (1965) for Montreal and was deemed sufficient for this work.

At the suggestion of Colten (1967), a nichrome wire having

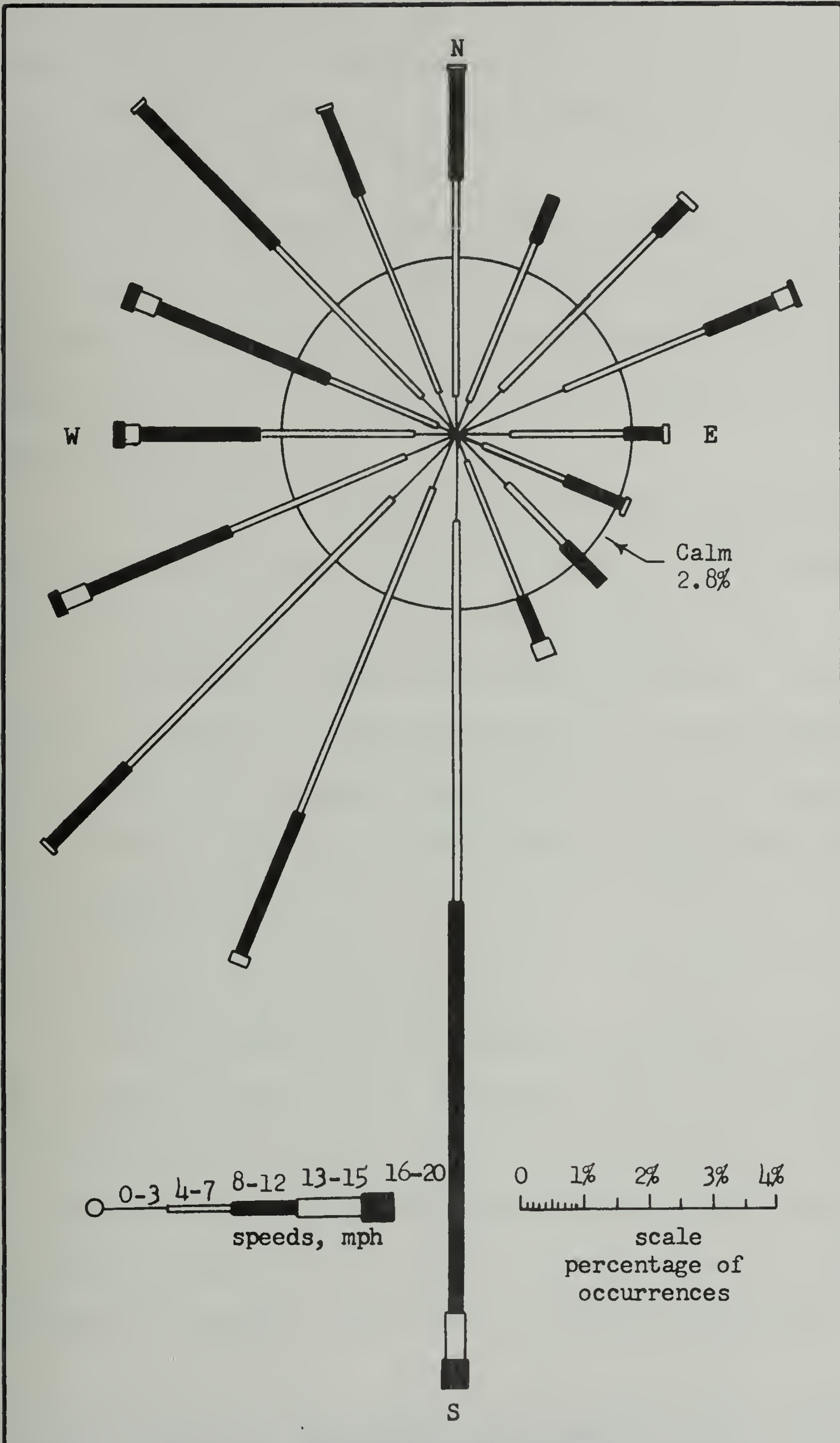

FIGURE 14. ANNUAL DAILY WIND ROSE, 1951-1957, CHAMPAIGN, ILLINOIS (From Changnon, 1959)

a copper braid shield and vinyl over jacket on the heater section was chosen.* Three sections of 210 m length, developing 3.17 kw on 240 v, were fabricated for installation.

In order to provide for a uniform heating of the surface, the heating cable was buried at a recommended depth of 8 cm (Colten, 1967). This caused a considerable reduction in available heat and is not a recommended practice. Placement of the cable on the surface would have produced the desired effect.

The pattern of placement of the heating cable was essentially that of concentric circles following the geometry of the urban complex. The three wires were placed in parallel at 15 cm intervals.

The power transmission line from the trailer to the plot was designed on the basis of the requirements of the heating cable, namely, 9.59 kw. Since the transformer supplied 60 amps at 240 volts, a number 6 A.W.G. wire was selected to provide for power transmission without undue voltage drop.

2. Design of roughness elements

It was mentioned in the literature review that the city imposes a roughness change on the environment. This increase in roughness is fundamental to the changes which the urban area makes on meteorological variables. Ideally, from theoretical considerations, the design of the model could, and perhaps should, be on the basis of some fundamental measurement of roughness rather than be a literal scale model.

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*Eazy Heat, Climate Control Division, The Singer Company, Lakeville, Indiana. Cat. No. EZ SC 720 44, Type G.

Because Kung (1963), Kutzbach (1961) and Plate and Quraishi (1965) had some success relating the geometry of roughness elements to the roughness parameter, the following relationship involving geometry was used in relating the model geometry to the prototype:

$$\frac{h_m \times \dfrac{\text{Plan area of element}}{\text{"Lot" area of element}}}{h_p \times \dfrac{\text{Plan area of building}}{\text{Lot area of building}}} = 0.01$$

Building "lath" (rough pine measuring 122 cm x 4 cm x 1 cm) was selected as the most economical and workable roughness material of known geometry. Approximately 2,500 pieces of this material were cut to form 17,000 individual elements for placement in the model.

The final element density was selected after a survey of Fort Wayne. The resultant configuration is illustrated in Figure 15. The business district of the model, the open rectangle in Figure 15, was differentiated from the residential areas by a change in h, the element height. The residential elements averaged 12.0 cm, while the business elements averaged 16.6 cm in height.

Lettau (1967) has proposed an empirical method for calculating roughness using the following formula:

$$z_o = \frac{h}{2} \quad \frac{\text{elevation area}}{\text{lot area}} \tag{46}$$

Using this formula a roughness length of 2.5 cm was computed for the model. A roughness length of approximately 2 m was computed for the prototype. The model was thus distorted in roughness with a scale of

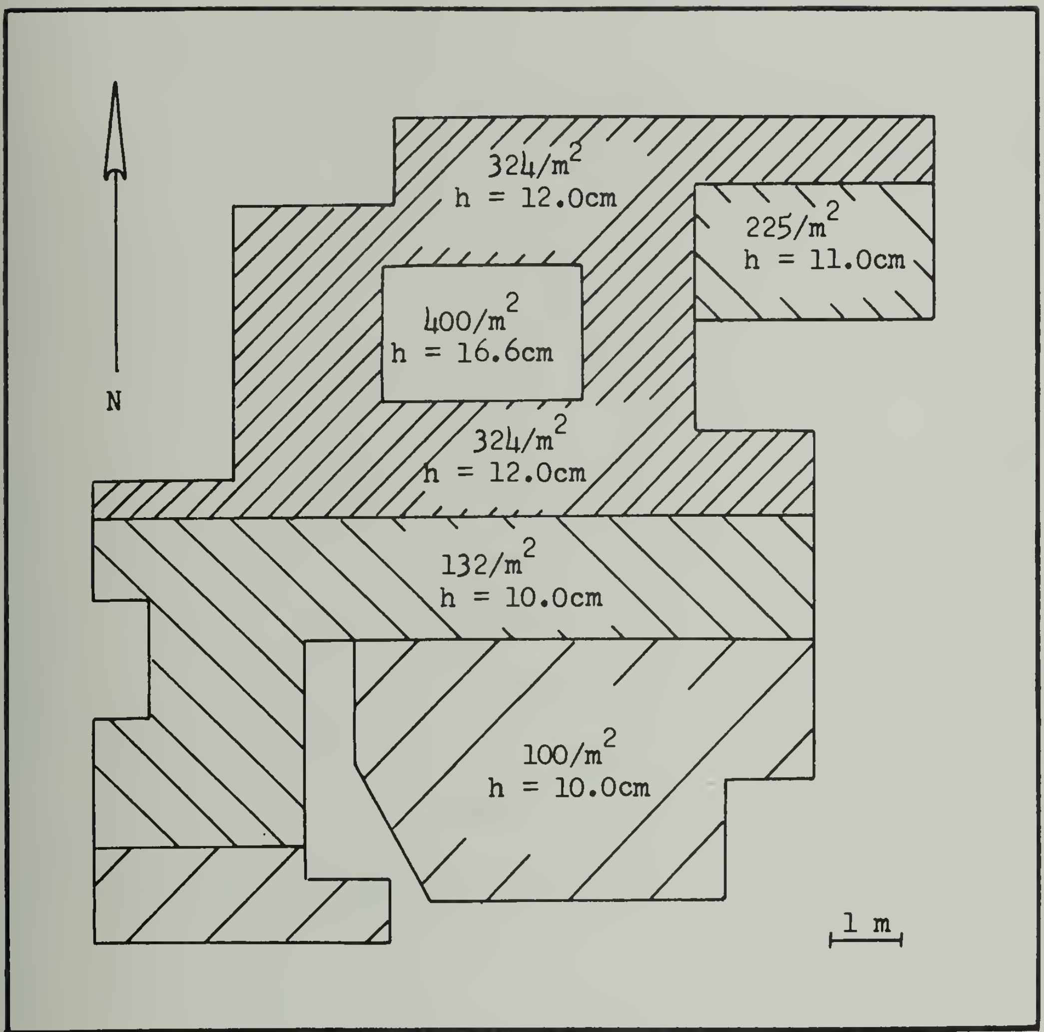

FIGURE 15. MODEL ELEMENT DENSITY

1:80 compared to the horizontal scale of 1:1000. No experiments were conducted to justify this distortion.

3. Albedo modification

It was recognized that the sensible heat flux, H, would be altered in the model because of the alteration of the albedo of the environment. Since the natural color of the building lath was essentially white, which would have reduced the heat input to the model during daylight hours, albedo modification was carried out.

Two steps were involved in reducing the albedo. The first step was to darken the lath. This was done by soaking each element in a creosote bath for a few seconds. The yellow-green color of the freshly creosoted wood aged to a dark brown in the presence of sun light. The second step was to cover the surface of the ground with "15 pound asphalt saturated felt" tar paper before erection of the roughness elements. This material not only darkened the interstices but also reduced the heat loss from evaporation.

E. Data Aquisition

In order to avoid local disturbances on the model from observers, all of the measuring systems were designed to transmit data to recording equipment located in the trailer (Figure 13).

The following three types of data aquisition systems were considered: (1) a fixed grid system with individual recording; (2) a traverse system with one sensing and one recording system; (3) a combination of the fixed and traverse system.

The prime advantage of the fixed grid system is synoptic observation. On the other hand, the multitudinous numbers of recorders required for this system made it prohibitive in terms of cost.

The relative economic advantage of the traverse system often makes it the most desirable system. However, the lack of synoptic observation and the difficulties in erecting a mechanical traversing system which would not cause local disturbances offset this prime advantage.

A combination of the fixed and traverse systems seemed to provide the desired solution. In this case it was decided to establish fixed sampling poles and sensors and traverse the system electrically by means of a stepping switch. This system provided near simultaneous observation without prohibitive expenditures for recording equipment.

A single channel Leeds and Northrup recorder* was available for recording temperature differences. The full scale response of this recorder was one second. Thus, it was decided that the minimum interrogation period at each sampling point would be two to three seconds. A cam driven by an electric clockmotor was selected to provide an interrogation period of 2.5 seconds.

A five pole, eleven position rotary stepping switch** provided 55 input slots to the recorder. The resulting cycling time for

*Leeds and Northrup Speedomax H (AZAR) recorder, with 2, 5, 10 and 100 mv spans Serial No. 62-23319-1-1.

**Automatic Electric, Type 44, PW 5605, gold plated contacts.

this system was 2.29 minutes. This was considered sufficiently rapid for the purpose of this research.

A reference system was constructed by dividing voltages from a series connection of two "pen light" batteries.

Stray voltages were minimized by employing gold plated switching decks and by providing for a common ground to the recorder for all data sampling.

The schematic wiring diagram is shown in Figure 16.

The behavior of the stepping switch was exceptional. No breakdowns occurred during any of the data runs, and maintenance considerations were limited to one occasion when the clockmotor-cam mechanism needed oiling. The maximum stray voltages encountered with the stepping switch amounted to only $\pm$ 20μv.

F. Temperature Measurement

1. Design of thermopiles

In order to achieve a large degree of sensitivity, differential thermopiles were designed to measure the vertical temperature profiles.

The two common wire combinations used in forming thermojunctions for meteorological purposes are copper-constantan and iron-constantan. The copper-constantan material has an output of 40 μv $^{o}C^{-1}$ and excellent service properties. The iron-constantan has a higher output, 50μv $^{o}C^{-1}$, but is subject to corrosion problems. The limited service and careful storage envisioned for the probes waived the corrosion consideration, and the iron-constantan was selected because

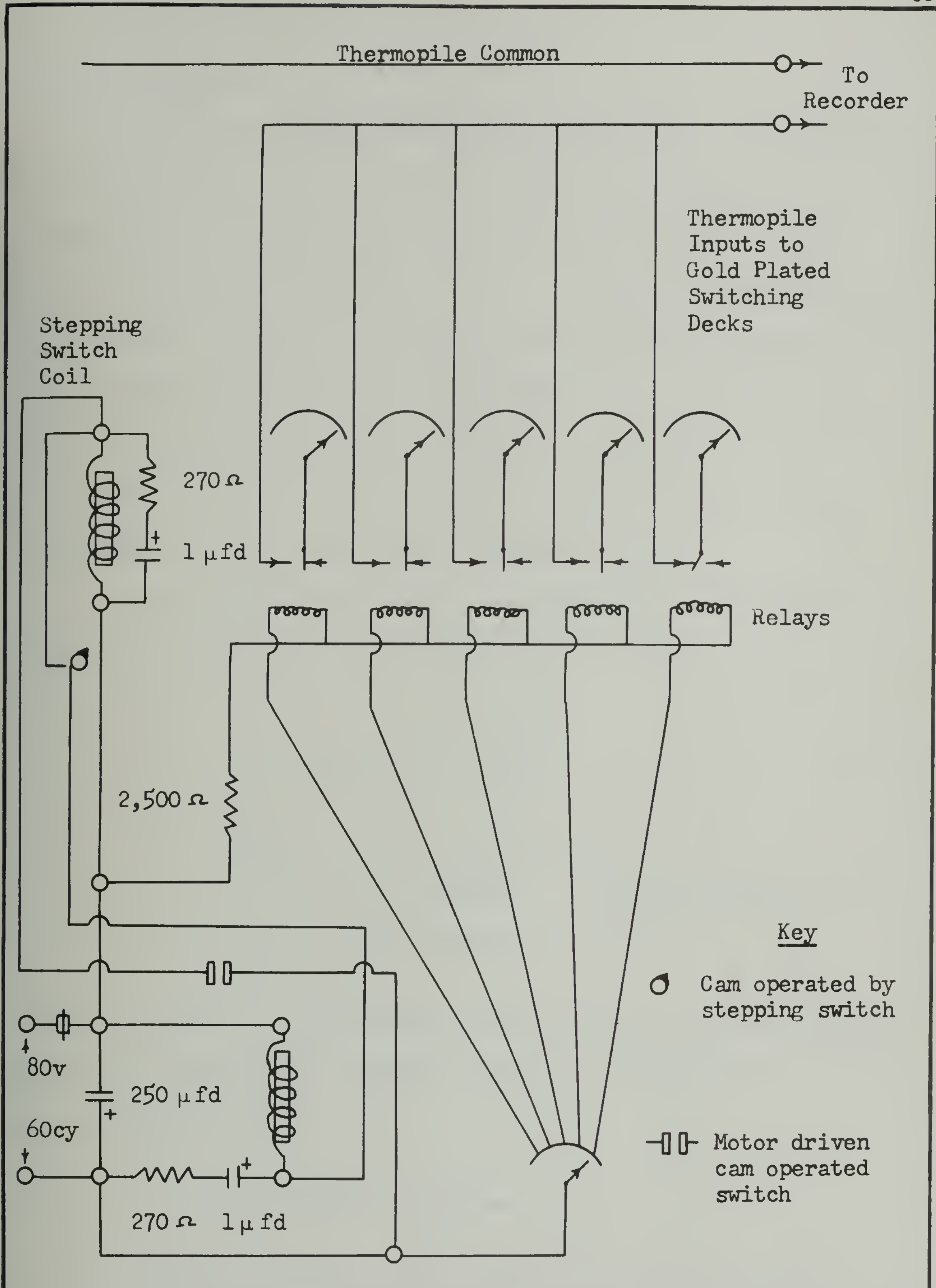

FIGURE 16. STEPPING SWITCH CIRCUIT

of its higher output.

The maximum temperature differences found in the Fort Wayne data were on the order of $1^{\circ}C$ to $2^{\circ}C$. Thus, differences of this order of magnitude had to be recorded on the Leeds and Northrup recorder. Since the minimum recorder span was 2 mv, considerable amplification was required. In order to facilitate data abstraction without a loss of sensitivity, twenty junction thermopiles were selected for the differential thermopiles. This resulted in an output of 1.0 $mv^{\circ}C^{-1}$ and a sensitivity of $0.02^{\circ}C$ per division on the 2 mv scale and a sensitivity of $0.05^{\circ}C$ per division on the 5 mv scale.

The choice of wire size for the thermojunctions was determined from the empirical formula given by Gill (1964):

$$\tau_{*} = 6000\ (d)^{1.34}\ (u)^{-0.40} \tag{47}$$

where τ_{*} = time constant, sec.

d = diameter of cylindrical sensor, in.

u = air speed, ft min^{-1}

The time constant, τ_{*}, was chosen on the basis of the given cycling period (137 seconds) and a 99.9% recovery of a step change in temperature (or $7\tau_{*}$). Thus,

$$\tau_{*} = \frac{137 \text{ sec}}{7} = 19.5 \text{ sec}$$

With a quiescent wind of 0.01 m sec^{-1} (1.97 ft min^{-1}) equation (47) was solved for the approximate diameter of the sensor.

The diameter was found to be 0.018 inches. Since two wires are used to make a thermojunction, a wire size which was half this value was selected (No. 30 B & S gauge*).

2. Design of radiation shielding

Two general methods are available to protect temperature sensing elements from radiation effects. In most measuring situations the aspirated shield has proven to be the best method of insuring accurate measurements. However, in a micrometeorological situation, such as in the model, the removal of air changes the temperature structure. For this reason some workers have argued for unaspirated shields. The unaspirated shield may give misleading results from shield radiation and air trapping which occur with strong solar radiation and weak winds. Since the experiments of this research were to be conducted under nocturnal conditions where these problems are minimized, the less complicated unaspirated shields were chosen.

The shielding material which is selected should have high reflecting properties. In the absence of solar radiation, polished metal shields have been found to be suitable for reflecting thermal radiation (Tanner, 1963). Heavy duty aluminum foil was chosen as a light weight, highly reflective shielding material.

3. Construction of thermopiles and shielding

The following procedure was adopted for construction of the

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*Leeds and Northrup Cat. Nos. 30-38-4 and 30-40-5 with enamel and single cotton cover insulation.

thermopiles. After 0.5 cm of thermocouple wire was stripped of its cotton cover, the enamel finish was sanded to insure good electrical contact. The wires were then twisted together and given a light solder* coating to insure a good electrical circuit. A resin base soldering flux was used to prevent acid corrosion of the thermo-junction.

The thermopiles were mounted on a 1 inch steel electric conduit to give elevations of 1 cm, 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 50 cm, 100 cm, and 150 cm from the ground. The poles were fit with connectors and a base pole was buried at the correct homologous point in the model. Thus, the thermopile system could be easily erected for each test and stored in the intervening periods.

Each of the thermojunctions in a thermopile was placed on a piece of masking tape leaving the junction exposed to the atmosphere. With all the junctions so placed, another piece of masking tape was placed on top of the wires to hold them in place. Each of the thermo-junctions thus maintained its integrity while measuring in the same horizontal plane.

The aluminum foil chosen for the radiation shielding was not sufficiently rigid to maintain itself in a cantilever position over the thermopile. By constructing a light aluminum right angle brace for support and laminating two pieces of foil together, a reasonably rigid radiation shield was constructed. The interior of each shield (bottom of the top one, top of the bottom one) was painted with flat black paint.

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*Weller - 60/40 activated rosin core for electronic work.

The shields were mounted so as to have a 0.5 cm spacing between the shield and the thermopile it was shielding.

4. Ambient temperature measurement

A copper-constantan thermocouple and recorder* were used to measure the ambient temperature at the one centimeter level at the location of the WANE-TV tower site in the model.

A mercury in glass thermometer was used to calibrate the thermocouple in a water bath.

5. Equipment characteristics

In general, the design of the thermopile system proved satisfactory. The thermopile time constants were determined in "still" air in the confines of the trailer. The average value for the time constants was found to be 42 seconds. If one recalls that the time constant varies approximately as the inverse square root of the wind speed equation (47), then it is reasonable to assume that the time constants would be considerably reduced when the thermopiles were exposed to other than "still" air.

Matching tests carried out with the poles suspended in a horizontal mode in the "controlled" environment of the trailer revealed that the sensitivity of the system was excellent and that the precision was within acceptable limits. The average error in precision was $\pm$ 0.07 $^{\circ}$C with a range of error of $\pm$ 0.10 $^{\circ}$C in the critical range

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*Leeds and Northrup Speedomax G -20°F to + 160°F
Serial No. A60 15307-1-1.

of usable data. (Temperature profiles taken under nonheat island conditions showed better correspondence, indicating the possibility that the "controlled" environment was not free of local disturbances.) A slowly increasing error was observed during the four months of testing but it was considered negligible (less than 0.01 ^{o}C/month) for the most part and where obvious errors were being introduced (dirty contacts, short circuiting, etc.) these were corrected.

Several difficulties were encountered with the system. One of the major difficulties was in maintaining the integrity of the circuits. The 30 gauge wire was highly susceptible to breaks during the fabrication stages, especially during mounting. After mounting, difficulty was often encountered with abrasion of the cotton-enamel insulation with consequent short circuiting. Most of these difficulties probably could have been overcome by using U strut for mounting rather than the conduit. A plastic insulation ("PVC"), although ruled out in this case because of economic considerations, would have saved considerable frustration.

No major difficulty was encountered with the ambient temperature measuring program with the exception of the failure of the reference dry cell in the recorder on one occasion.

G. Wind Measurement

The choice of a wind measuring system was a compromise between technical requirements and economic feasibility.

Because of the weak wind conditions under which the experimental program was to be conducted, a highly sensitive wind system was

desired. In addition, the well known height variation of the atmospheric wind speed made it necessary to measure the wind speed at several elevations. Although the windmill type anemometer system is recognized as the most sensitive, it is generally the most expensive. Fortunately, cup anemometers of relatively high sensitivity may be specified at a reasonable cost.

A wind profile system* was selected to meet the following specifications:

Wind speed range:	0 - 14.5 m sec^{-1}
Starting speed:	0.1 m sec^{-1}
Distance constant:	1.0 m
Anemometer cups:	four, conical, plastic, 5 cm diameter with reinforced metal edge, weight 7 g or less
Transmitter housings:	brass mounted on 25 cm arms
Signal output:	photoelectric
Indication:	electromechanical, no relays

The anemometer cups were mounted at fixed levels of 25, 50, 100 and 200 cm.

The errors associated with cup anemometry are numerous (Bernstein, 1967; Frenzen, 1966; MacCready, 1966; Tanner, 1963). The over-running often encountered with cup anemometers is generally

*C. W. Thornthwaite Associates Wind Profile System 104 Serial No. CWT 637.

considered a function of the weight (Frenzen, 1966). The light weight cups specified for the system reduced this type of error. By choosing a photoelectric sensor, the effects of friction on the starting speed were reduced and the lower operating range was considerably extended. Although some difficulties have been reported because of cup mountings interferring with flow patterns, Tanner (1963) indicates that the wind system selected introduces the least error from this source. By operating with the cup arms oriented into the wind as suggested by Stearns (see Tanner, 1963) errors introduced by flow around the mast were eliminated.

The anemometer matching technique suggested by Tanner (1963) was carried out to obtain a relative calibration of the wind system.

Since the portable wind profile system normally uses a 12 volt DC power supply, a rectifier was built to enable the use of the AC power supply in the trailer. Figure 17 shows a circuit diagram of the rectifier.

The behavior of the system was quite satisfactory.

H. Net Radiation Measurement

The following characteristics were deemed essential for the net radiometer: low time constant, high enough output for easy recording, minimal effects of wind and temperature, non-ventilated.

A shielded net radiometer was made available* which more than satisfied the above requirements. The time constant of the net

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*Fritschen Type produced by the U. S. Water Conservation Laboratory Serial No. 204.

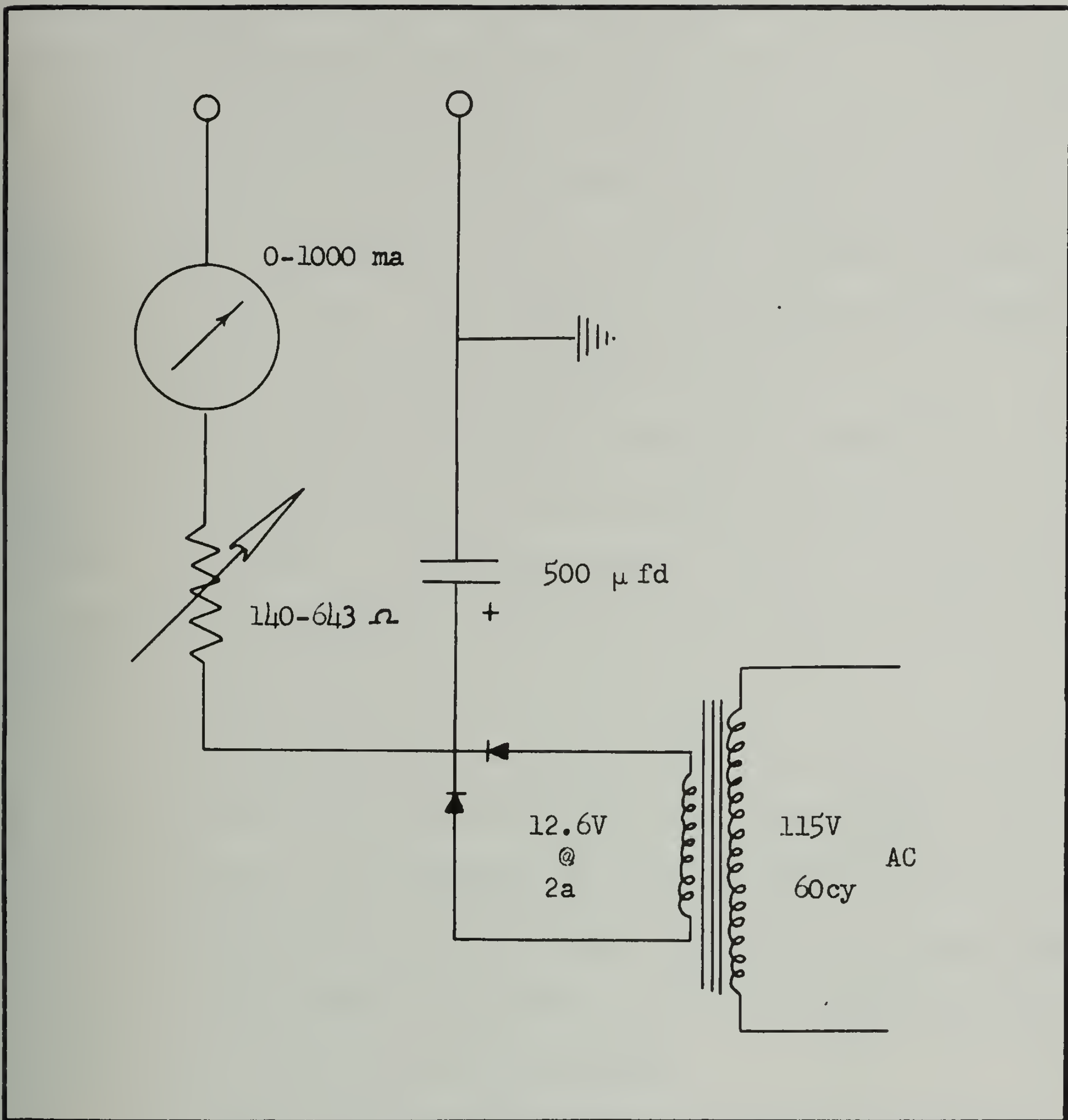

FIGURE 17. DC POWER SUPPLY

radiometer was 12 seconds. The output was designed for optimum use on a $\pm$ 5 mv recorder with a calibrated output of 2.85 mv ly^{-1} min. A 2 mil thick polyethylene film was used as the shielding material to minimize the effects of wind. In addition the system included a compensated thermal transducer to reduce the effects of ambient temperature (see Fritschen, 1965). The output was sampled with the stepping switch and recorded along with the temperature profiles.

It was considered advisable to provide a capacity to measure the net radiation over both the grass and the built-up structure of the model. A television antenna rotator** was selected as the means for accomplishing this task. This allowed for remote operation from the trailer.

The net radiometer was mounted on a boom extending 1m from the antenna rotator at an elevation of 60.5 cm from the ground. In this configuration it was determined that the net radiometer could not "see" the antenna rotor and would not be biased by its temperature. Measurements of net radiation were taken once over the model and once over the grass area for each sampling sequence.

Many difficulties were encountered with the net radiation measurement. The major problem was with condensation on the polyethylene shield of the net radiometer. Although the inside remained dry, the exterior on occasion was literally covered with water (and in the later tests with frost). Since moisture has a significant effect on the measurement (Fritschen, 1963), this necessitated an exasperating

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**J. C. Penney Company catalog number A 858-0193 A.

number of trips to the model between data sampling for drying operations.

Another source of trouble was probably the result of the use of the antenna rotor. Although the time constant of the net radiometer was 12 seconds, it was often obvious that any reading taken less than 5 minutes after a rotation was in error. Readings taken 5 minutes or longer after rotation were consistently reproducible while those taken at an interval of 2 minutes (10 time constants) to 5 minutes were not. This was considered to be the result of either of two factors: (1) conductive and convective heat transfer from the rotation and/or (2) conductive and convective heat transfer from swaying as a result of the termination of the rotation.

I. Soil Heat Flux Measurement

A soil heat flux disk* was located in the model approximately one meter upwind of the model GT tower location. The soil heat flux disk was placed just below the tar paper. The output was sampled with the stepping switch and recorded with the temperature profiles. The behavior of this piece of equipment was exceptionally good.

J. Experimental Procedure

During the four months of data collection the grass layer upwind of the model was kept mowed to a level of 4 to 5 centimeters. The mowed area extended 17 meters from the model in the upwind direction to unmowed grass which was at a height of approximately 30

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*Thornthwaite Model 610 No. V2 5.18 mv ly^{-1} min.

centimeters. From theoretical discussions of the effect of change in roughness on the wind profile (Panofsky and Townsend, 1964) this distance was deemed sufficient to allow the lower 1.5m of the profile to come substantially to equilibrium by the time it reached the model.

The initial step in preparing for an experiment was to determine if a test was to be conducted. If the twenty-four hour forecast indicated the existence of a high pressure center in the proper position to yield weak southerly winds, then the heating cables were activated. An additional forecast for cloud cover, wind speed and wind direction was made six hours before sundown. If the six hour forecast indicated clear skies with southwesterly winds diminishing to less than eight miles per hour, the operational procedure was initiated.

Approximately an hour and a half prior to sundown instrument placement was begun. The anemometer cups and net radiometer were mounted, thermopile poles erected and telemetering cables for the wind and ambient temperature sensor were laid to the trailer. If all the equipment was found to be functioning satisfactorily, data collection began at sundown and continued at half hour intervals.

The sequence for any sample consisted of the following steps:

1. Read and initiate wind profile register and stop watch.

2. Initiate profile sampling and continue for 2 cycles.

3. Terminate profile sampling.

4. Terminate wind sample after 10 minute interval, read and compute wind speeds.

5. Take surface observations of barometric pressure, temperature, relative humidity, cloud cover and type, visibility, and note wind direction. (A check on the general wind direction was made by observing the smoke trail of an extinguished candle.)

The ambient temperature record was kept continuously and "time of sample" marks were made on the strip chart for later abstraction.

K. Analytical Procedure

1. Analysis of prototype data

a. Selection of temperature profiles

Approximately 60 hours of data from 17 periods in the months October, 1965 through February, 1966 were available from the experiments conducted at Fort Wayne. Although the heat island effect could be observed in all of the profiles, a large majority of cases did not exhibit the "typical" rural inversion and subsequent modification which has caused so much difficulty with the diffusion equations (Turner, 1964; Pooler, 1966). Because of this fact and because of experimental limitations (namely, the ability to supply enough heat), only those periods where the WANE television tower profiles were nonnegative were selected for attempted profile modeling. Table 8 summarizes those periods which were found satisfactory based on this criterion.

TABLE 8

SELECTED PROTOTYPE DATA PERIODS

Test No.	Date	Hour	$T_{61m-12.2m}$
65-1	24 Oct. 65	2000	0.2
65-1	24 Oct. 65	2030	0.2
65-1	24 Oct. 65	2115	0.5
65-2	24 Oct. 65	2115	0.0
65-8	6 Dec. 65	1830	0.0
65-8	6 Dec. 65	2000	0.0
65-18	4-5 Feb. 66	0000	0.0

b. Computation of heat flux

Most of the characteristic variables for computing the model law discussed under theoretical concepts could be determined from existing measurements or simple, straightforward computations. A definite exception was the determination of a value for the heat flux, H.

Microclimatological determinations of the heat flux can be determined with the aid of the definitions of the energy balance equation, equation (38). In an open field the heat contribution from human activity is lacking and, if one either measures evaporation or, as in this case, restricts the consideration to nocturnal periods

where the evaporation term may be neglected, equation (38) reduces to the following (Dyer, 1961):

$$R_n = G + H \tag{48}$$

If one can measure the net radiation and the soil heat flux, then the turbulent heat flux may be calculated.

Unfortunately, neither net radiation nor soil heat flux measurements were taken in Fort Wayne. This forced the consideration of alternative definitions.

The expression given by equation (45) does not depend on any variable which could not readily be obtained from the Fort Wayne data, and it was chosen as the means of estimating a value for the turbulent heat flux. All variables were selected at the GT site.

c. Selection of other characteristic variables

The remaining characteristic variables which were required for computation of the model law were selected from readily available data. The characteristic temperature was taken to be the temperature measured at 15 m at the location of the GT tower. With dew point measurements and the above value of the temperature, a characteristic air density was computed. The characteristic variables which were required for computation of the model law were selected from readily available data. The characteristic temperature was taken to be the temperature measured at 15 m at the location of the GT tower. With dew point measurements and the above value of the temperature, a

characteristic air density was computed. The characteristic wind speed was taken from the pilot balloon computation at approximately 1000 m elevation.

d. Estimating contributions to heat island

Since no radiation measurements existed for the Fort Wayne area, an alternative approach was developed for estimating the solar heat input to the heat island.

The standard pyranometer records solar, R_S, plus diffuse, R_D, radiation directly. If pyranometer records are available, the net radiation input may be estimated directly. Since pyranometer data were not available at Fort Wayne, radiation data were obtained for three stations surrounding Fort Wayne at approximately the same latitude (E.S.S.A., 1965a; 1966a). The three stations were Cleveland, Ohio; Argonne, Illinois; and Indianapolis, Indiana.

The first step in the estimating procedure was to determine the air mass equivalence of the three observation stations and Fort Wayne. If two or more of the stations were deemed equivalent, a plot of percent sunshine (E.S.S.A., 1965b; 1966b) versus percent radiation was made, and the sunshine record from Fort Wayne was used to estimate the percent radiation. The percent sunshine records were considered to be reasonably reliable (Merritt, 1966). If no two stations could be found under an equivalent air mass, the nearest day exhibiting equivalence was selected for the estimate.

The estimates of the contribution of human activity, Q, to the heat island were made from the data sources listed in Table 9.

TABLE 9

DATA SOURCES FOR ESTIMATES OF HUMAN ACTIVITY HEAT CONTRIBUTION

Components of heat contribution	Data Source
Space heating, s	Karch, 1967 McGinnis, 1967
Industrial heating, i	Karch, 1967
Automotive heating, a	Traylor, 1967 Gold, 1954
Power plant heating, p	Traylor, 1967 Morton, et al., 1956
Metabolic heating, m	Traylor, 1967 Guyton, 1961

2. Analysis of model data

a. Classification of profiles

If one were to conduct model studies in a wind tunnel, he would be able to select those conditions of wind speed, geometry and heat flux which were in scaled proportion to the atmospheric conditions which he desired to simulate. In the case of autogenous atmospheric simulation one is dependent upon the atmosphere to supply the scaled variables. Therefore, a large amount of data must be collected and a classification procedure applied to obtain working data.

The first step in the classification procedure was to eliminate from consideration those cases in which no model heat island effect was observed. A model heat island effect was defined as any

case where the temperature differential $T_{15\ cm} - T_{10\ cm}$ of the model GT tower (urban) was less stable than that of the model WANE tower (rural). A summary of the data periods and a classification of those having a heat island effect is given in Table 10.

In order to avoid the impossibility of trying to compare dissimilar stability situations in the model and prototype, the profiles which remained after discarding the non-heat island cases were divided into two classes: those in which the profiles from the model WANE $T_{15\ cm} - T_{10\ cm}$ were positive (stable) and those in which the profiles were negative (unstable). The result of this classification is listed in Table 10 under the heading "Profile Sign."

b. Computation of the heat flux

The heat flux, H, was computed from the net radiation and soil heat flux measurements according to the method of Dyer (1961).

$$H = R_N - G \tag{49}$$

c. Selection of characteristic variables

The remaining characterizing variables were chosen in the following manner: (1) Characteristic temperature - from temperature measurement at one centimeter elevation at model WANE site; (2) Characteristic density - computed from (1); (3) Characteristic wind speed - wind speed measured at one meter elevation and one meter upwind of the model.

3. Determination of the scale factor

The determination of the scale factor, K_L, was made based

TABLE 10

CLASSIFICATION OF MODEL TEMPERATURE PROFILES

Date	Sky Cover, tenths	Cloud type	Wind Speed m sec^{-1}	Wind Direction	Heat Island Effect	Profile Sign[a]
19 Sept.	10	Cu	0.71	SW	yes	-
25 Sept.	0	-	2.59	SW	no	+
30 Sept.	0	-	0.50	SW	yes	-
11 Oct.	0	-	0.41	SSW	yes	-
12 Oct.	9	Cs	2.59	SE	no	+
14 Oct.	0	-	1.47	ESE	no	+
19 Oct.	5	Cs	0.76	SW	yes	+
21 Oct.	0	-	0.42	SW	yes	-
9 Nov.	9	Cu	1.80	SW	no	+
3 Dec.	0	-	1.34	SW	yes	+
16 Dec.	7	Cs	1.55	S	no	+

[a]Profile sign = Sign of $T_{15\ cm} - T_{10\ cm}$ at site of model WANE tower.

on the theoretical concepts expressed in Chapter IV.

The basic relationship of equation (32) was used to relate the temperature profiles of the model and prototype:

$$\left(\frac{\Delta T}{\Delta z} + \Gamma\right)_p = K_L \left(\frac{\Delta T}{\Delta z} + \Gamma\right)_m \tag{32}$$

In the case of the model, the adiabatic lapse rate, Γ , is negligibly small in comparison to $(\Delta T/\Delta z)_m$ and was, therefore, neglected in the analysis. A displacement plane of ten centimeters was used as a reference in carrying out the determination because of the basic assumption used by Monin and Obukhov (1954) in deriving the characteristic scale length of turbulence, L_* (i.e. that the similarity principle be applied in the atmosphere down to the level of the surface elements but not within them.)

The first attempts to determine the scale factor were made on the basis of the model law alone. That is values of K_L were calculated from the relationship

$$K_L = \frac{(K_U)^3}{K_H} \tag{33}$$

and the model WANE temperature profiles were plotted for comparison with the prototype on the basis of the scaled relationship

$$\frac{\Delta T}{(\Delta z)\ \frac{1}{K_L}}$$

The result of this effort confirmed the concept discussed in Chapter IV, namely that since the scale geometry is fixed by the physical characteristics of the prototype and the model constructed to represent it, only that combination of variables which yields an equivalent value of K_L will provide similitude. In this case it appeared that K_L had a value of approximately 0.001.

From the results of the initial profile comparisons, an alternative method of model profile selection was developed. The final selection technique consisted of searching for values of U and H such that a calculated value of K_L of approximately 0.001 would result. (In a wind tunnel one would, of course, be able to set these conditions so that this technique remains within the integrity of modeling concepts.) The model profiles were then plotted with a scale factor of 0.001 and the resultant profile configurations compared with the prototype profiles.

4. Validation of the scale factor

With the scale factor determined by the above method, the model GT tower profile was compared with the prototype, and if a third prototype profile was available this also was compared with the corresponding model profile. If these profiles agreed, it was assumed that the scale factor had been validated.

5. Verification of the model law

In an attempt to verify the model law, the standard error of the model profile in estimating the prototype was computed. This standard error of estimate was then compared by correlation analysis

with the deviation of the calculated K_L from the value used in plotting the curves, namely $K_L = 0.001$.

6. Determination of characteristic length

Because only one model geometry was examined in this research, no reasonable assessment could be made of "the" geometric length which characterizes the behavior of the systems.

CHAPTER VI

RESULTS AND DISCUSSION

A. Introduction

The existance of the urban heat source and its consequent modification of atmospheric stability was, of course, fundamental to the concept of this research (Figure 18).

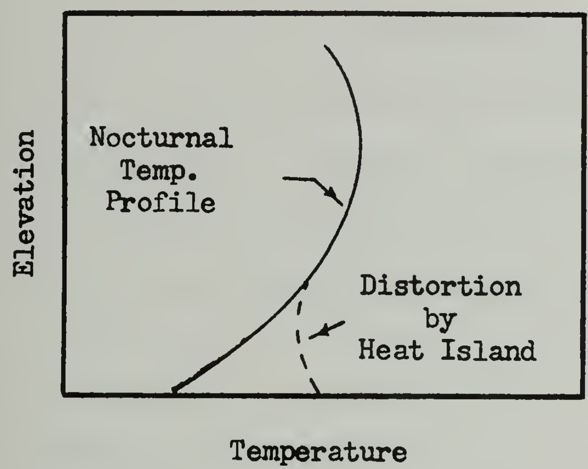

FIGURE 18. URBAN MODIFICATION OF TEMPERATURE PROFILES

In essence, the requirement of this work was to show that a micro-meteorological model could perform a temperature profile distortion similar to the one produced by the full scale prototype.

In the following discussion the results of the literature survey and data analysis, in conjunction with the energy balance equation, are used to qualitatively assess the relative importance of the various factors contributing to the Fort Wayne heat island effect. The general character of the prototype and model heat islands is

discussed, and the relative success of the experiments in achieving the desired temperature profile distortion is considered.

B. The Physical Basis of the Heat Island

1. Radiation

It has often been reported (Lowry, 1967) that the city structure "screens" nighttime radiation losses and thereby promotes the heat island effect. The arguments based on Figure 5 and Table 6 showed that this effect is of little or no consequence. However, it is expected that a nighttime urban mist and haze layer would significantly increase counter radiation (R_L) over the long wave radiation loss (σT^4). In a relatively unpolluted atmosphere such as the one over Fort Wayne, this would probably not be of much consequence.

2. Heat storage

Net radiation is composed, of course, not only of the radiation balance but also of the surface energy balance ($R_N = G + E - Q + H$). One recognizes the storage of radiative heating (G) in the warmth of a concrete pavement in the evening following a hot summer day. Although some authors (Kratzer, 1956; Daniels, 1965) feel that cities contain a large proportion of materials such as steel, concrete and granite which greatly increase heat absorption capacity, this generalization does not stringently apply to the Fort Wayne complex. Table 11 is a comparison of some of the estimated average thermal properties of Fort Wayne and the surrounding countryside of Allen County.

TABLE 11

ESTIMATES OF AVERAGE THERMAL PROPERTIES

Thermal property	Fort Wayne	Allen County
ρ, g cm^{-3}	1.66	1.52
C_p, g-cal g^{-1} $^{o}C^{-1}$	0.28	0.36
λ, g-cal cm hr^{-1}cm^{-2} $^{o}C^{-1}$	8.2	6.3

The amount of heat required to raise the temperature of a substance is proportional to its conductive capacity. Conductive capacity is defined by equation (50):

$$\text{Conductive Capacity} = \sqrt{\rho \, C_p \, \lambda} \tag{50}$$

This means that equal heat supplied to the city and country will raise the average surface temperature approximately 5 percent more in Fort Wayne than in Allen County.

Some values of the solar plus diffuse radiation are listed in Table 12. These values are averaged over the 24 hour period to give units of ly min^{-1}. The dates were selected to coincide with days on which data was taken in the prototype study (Hilst and Bowne, 1966).

TABLE 12

ESTIMATED HEAT STORAGE
FORT WAYNE, INDIANA
1965 - 1966

Date	Solar + Diffuse Radiation ly min^{-1}
24 Oct.	0.146
26 Oct.	0.205
8 Nov.	0.090
16 Nov.	0.115
17 Nov.	0.083
29 Nov.	0.156
5 Dec.	0.142
6 Dec.	0.035
6 Jan.	0.052
10 Jan.	0.163
13 Jan.	0.024
23 Jan.	0.142
27 Jan.	0.104
28 Jan.	0.153
29 Jan.	0.128
4 Feb.	0.190

3. Evaporation

Although precipitation-storage relationships were not available for the Fort Wayne area, some qualitative assessment of the importance of evaporation may be inferred from other sources.

A significant portion of incoming radiation is consumed by evaporation and evapotranspiration processes. Geiger (1965) estimates that as much as 86 percent of the energy may be used in this manner.

Insufficient observation has led many to the opinion that the city is like a desert because precipitation is carried off from the pavement via sewers. While this may be true in the "inner cities" and business areas and, perhaps, accounts for their relatively large temperature differentials, for most U. S. cities, which are relatively open, the lawns act as a sponge. Smith (1967) has found that, for cities of the composition of Fort Wayne, only 10 percent of the precipitation is actually lost to the sewers.

4. Heat contribution from human activity

Schmidt (1971) was, perhaps, the first to estimate the contribution of human activity to the reservoir of heat energy (Q). His results and those of subsequent workers are listed in Table 13.

TABLE 13

HEAT CONTRIBUTION FROM HUMAN ACTIVITY

Q ly min^{-1}	Averaging Period	Place	Latitude, °N	Source
.143	Winter night	Montreal	45	Summers (1965)
.036	Spring night	San Francisco	37.5	Perkins (1961)
.035	year	Germany	51	Kratzer (1936)
.032	year	Berlin	52.5	Schmidt (1917)
.023	year	Vienna	48	Schmidt (1917)
.019	Winter day	Edmonton	55	Daniels (1965)
.008	Summer day	Edmonton	55	Daniels (1965)

Although various authors considered various sources contributing to Q, none computed values for all the factors listed in equation (43), repeated here for the purpose of discussion.

$$Q = s + i + a + p + m \tag{43}$$

where s = space heating

i = industrial process heating

a = automotive heat production

p = power plant heat losses

m = animal metabolic activity

Values for a, p and m were computed from average statistical data available for Fort Wayne.

The average weekday volume of vehicles for Fort Wayne is approximately 15,250 vehicles or about 625 cars operating every hour (Traylor, 1967). The average heat output of an automobile is 63,000 kg-cal hr^{-1} (Gold, 1954). The automotive heat production thus amounts to 0.000614 ly min^{-1}.

Assuming a large power plant heat loss of 500,000 kw (Morton, et al., 1956), a heat contribution of 0.0068 ly min^{-1} results.

Guyton (1961) estimated that a 70 kg man sitting at rest expends 100 kg-cal hr^{-1} of energy. Approximately one third of this energy is consumed in evaporation processes and, therefore, 67 kg-cal hr^{-1} is contributed to Q. Thus, for Fort Wayne's 179,369 population (Traylor, 1967), a heat contribution of about 0.00046 ly min^{-1} results. Schmidt (1917) gives an estimate of 0.004 to 0.005 ly min^{-1} for the cities he examined. The higher population density existing in Berlin and Vienna as well as a rather high animal population (9,500 cows; 35,000 horses) accounts for the difference in estimates.

The total of a, p and m amounts to about 0.008 ly min^{-1} for Fort Wayne. From the records of the Northern Indiana Public Service Company (Karch, 1967) and the estimates of the Shell Oil Company (McGinnis, 1967) values of industrial and space heating were estimated (Table 14). The dates were selected to coincide with days on which data were taken in the prototype study (Hilst and Bowne, 1966).

Although the efficiency of space heating equipment is about 60 percent to 70 percent, the unused heat value of the fuel is

TABLE 14

HEATING FROM FUEL CONSUMPTION
FORT WAYNE, INDIANA
1965 - 1966

Date	Gas Space Heating ly min^{-1}	Oil Space Heating ly min^{-1}	Total Space Heating ly min^{-1}	Q^a ly min^{-1}
24 Oct.	0.0053	0.0019	0.0072	0.018
26 Oct.	0.0041	0.0015	0.0056	0.017
8 Nov.	0.0050	0.0018	0.0068	0.018
16 Nov.	0.0057	0.0021	0.0078	0.019
17 Nov.	0.0075	0.0028	0.0103	0.021
29 Nov.	0.0091	0.0033	0.0124	0.023
5 Dec.	0.0059	0.0022	0.0081	0.019
6 Dec.	0.0083	0.0030	0.0113	0.022
6 Jan.	0.0081	0.0030	0.0111	0.022
10 Jan.	0.0108	0.0040	0.0148	0.026
13 Jan.	0.0086	0.0032	0.0118	0.023
23 Jan.	0.0113	0.0042	0.0155	0.027
27 Jan.	0.0122	0.0045	0.0167	0.028
28 Jan.	0.0123	0.0045	0.0168	0.028
29 Jan.	0.0125	0.0046	0.0171	0.028
4 Feb.	0.0111	0.0041	0.0152	0.026

[a]Q = total heat contribution from human activities.

generally lost through the chimney to the atmosphere and the net result is that all heat eventually reaches the atmosphere. It was assumed, therefore, that all the fuel supplied was converted to its rated heat value. The oil consumed for industrial processes amounted to only 1 percent of the total oil consumption (McGinnis, 1967) and was not calculated. The industrial process consumption of natural gas was approximately 0.00278 ly min^{-1}.

It is interesting to compare the estimates listed in Table 12 and 14 with the relative findings of Schmidt (1917) and Daniels (1965) on the relative importance of human activity in contributing heat. This comparison is shown in Table 15, where $R_S + R_D$ is the solar plus diffuse radiation contribution, and Q is the sum of the effect of human activity, and G is the heat storage.

In the winter months the heating resulting from human activity appears to constitute about 25 percent of the contribution from solar plus diffuse radiation. Although this is in general agreement with Schmidt's findings for a yearly average contribution, it falls far below the values he computed for the winter months (See Table 16).

TABLE 15

RELATIVE CONTRIBUTIONS TO FORT WAYNE
HEAT ISLAND
1965 - 1966

Date	$\frac{Q}{(R_s + R_D)}$	$Q + (R_s + R_D)$ ly min^{-1}
24 Oct.	0.12	0.27
26 Oct.	0.09	0.30
8 Nov.	0.20	0.29
16 Nov.	0.17	0.29
17 Nov.	0.25	0.33
29 Nov.	0.15	0.31
5 Dec.	0.13	0.27
6 Dec.	0.63	0.66
6 Jan.	0.42	0.47
10 Jan.	0.16	0.32
13 Jan.	0.96	0.98
23 Jan.	0.19	0.33
27 Jan.	0.27	0.37
28 Jan.	0.18	0.33
29 Jan.	0.22	0.24
4 Feb.	0.14	0.33
Average	0.268	0.38

TABLE 16

SPACE HEAT TO SOLAR HEAT RATIOS
VIENNA 1917[a]

Month	$\frac{Q}{R_s + R_D}$
November	1.15
December	2.22
January	1.45
February	0.64

[a]From Schmidt, 1917

The sum of heat from human activity plus solar and diffuse radiation heat input averaged about 0.38 ly min^{-1} for the dates investigated in Fort Wayne. The July radiation heat input computed for Cleveland, Ohio (which is at approximately the same latitude as Fort Wayne) is approximately 0.31 ly min^{-1}. Thus, for Fort Wayne, the value of Q + (R_s + R_D) does not appear to remain the same on a yearly average as suggested by Daniels (1965).

C. The Heat Island in the Prototype and in the Model

1. Characterization of heat island

Duckworth and Sandberg (1954) developed three parameters for classifying the magnitude of the heat island effect. The first and most straight forward measurement is that of the urban-rural temperature

differential, D. This is the difference between the maximum and minimum observed temperatures.

To provide some measure of differential intensity of the heat island, Duckworth and Sandberg (1954) developed the expression $R/\Delta T$. $R/\Delta T$ is defined as the least distance along which an arbitrary temperature change ($1^{\circ}F$) might be observed. A more meaningful parameter is the inverse of this, namely, $\Delta T/R$. This is defined as the maximum observed temperature gradient.

Duckworth and Sandberg (1954) determined the extent of the urban temperature effect by defining an area, A, about the urban center. This is an area which has a temperature more than $2^{\circ}F$ greater than the average as determined from the maximum and minimum temperatures of the urban-rural traverse. The results of Duckworth and Sandberg (1954) are summarized in Table 17.

TABLE 17

CHARACTERIZATION OF THREE HEAT ISLANDS[a]

	San Francisco	San Jose	Palo Alto
D, $^{\circ}C$	5.5 to 6.7	3.9 to 5.0	2.2 to 3.3
$\Delta T/R$, $^{\circ}C\ km^{-1}$	.86 to 1.15	1.4 to 2.3	2.3 to 6.9
A, km^2	10.4 to 15.5	3.9 to 5.2	.25 to .78
Population	784,000	101,000	33,000

[a]After Duckworth and Sandberg, 1954

If one uses the population of Fort Wayne (179,369) as an index of the effectiveness of the city in creating a heat island, one would expect to find that Fort Wayne is as effective in creating an urban heat island as San Jose.

Although a dense horizontal temperature record was not available for computation of Duckworth and Sandberg's "A", sufficient information was available to compute values of D and $\Delta T/R$ for each of the prototype test periods selected for the modeling attempts. These data are presented in Table 18.

From the values of D and $\Delta T/R$, Fort Wayne appears to be as effective in creating a heat island as one might have hypothesized on the basis of population. The Fort Wayne heat island is, thus, neither abnormally strong nor abnormally weak for a city of its size.

TABLE 18

CHARACTERIZATION OF FORT WAYNE HEAT ISLAND

Date and Hour	D, ^{o}C	$\Delta T/R$, $^{o}C\ km^{-1}$
24 Oct. 2000	3.7	1.54
24 Oct. 2030	4.1	1.46
24 Oct. 2115	4.1	1.33
26 Oct. 2115	3.7	1.25
6 Dec. 1830	3.7	1.42
6 Dec. 2000	3.3	1.42
4-5 Feb. 0000	3.1	.96

2. Effect of the heat islands on vertical temperature profiles

The data selected from the report of Hilst and Bowne (1966) provided the "characteristic" modification of the vertical temperature profile mentioned in the introduction. The typical effect of the urban area is illustrated in Figure 19. The WANE-TV tower upwind of the city, in rural environs, recorded an inversion temperature gradient. As the air mass passed over the heat island the temperature profile was distorted to a near neutral lapse rate which was recorded by the GT tower located in the urban business district. As the air mass then moved across the city and into downwind rural environs the temperature profile began to recover to the upwind condition. The rural downwind wiresonde, thus, recorded an isothermal temperature gradient which lies between the other profiles.

The micrometeorological model was able to perform a similar modification on a reduced scale. That is, it could create a more unstable atmosphere than that occurring at the upwind rural station. This effect is illustrated in Figure 20. In this example, the model WANE tower recorded a lapse condition. As the air mass passed over the heat island the profile was distorted to a stronger lapse condition. As the air mass moved away from the heat island the profile (model Wiresonde II) began to attain its upwind rural configuration.

3. Behavior of the heat islands

The amount of data available for correlating meteorological variables with the prototype or model heat island effects was too limited to be of any climatological significance. On the other hand,

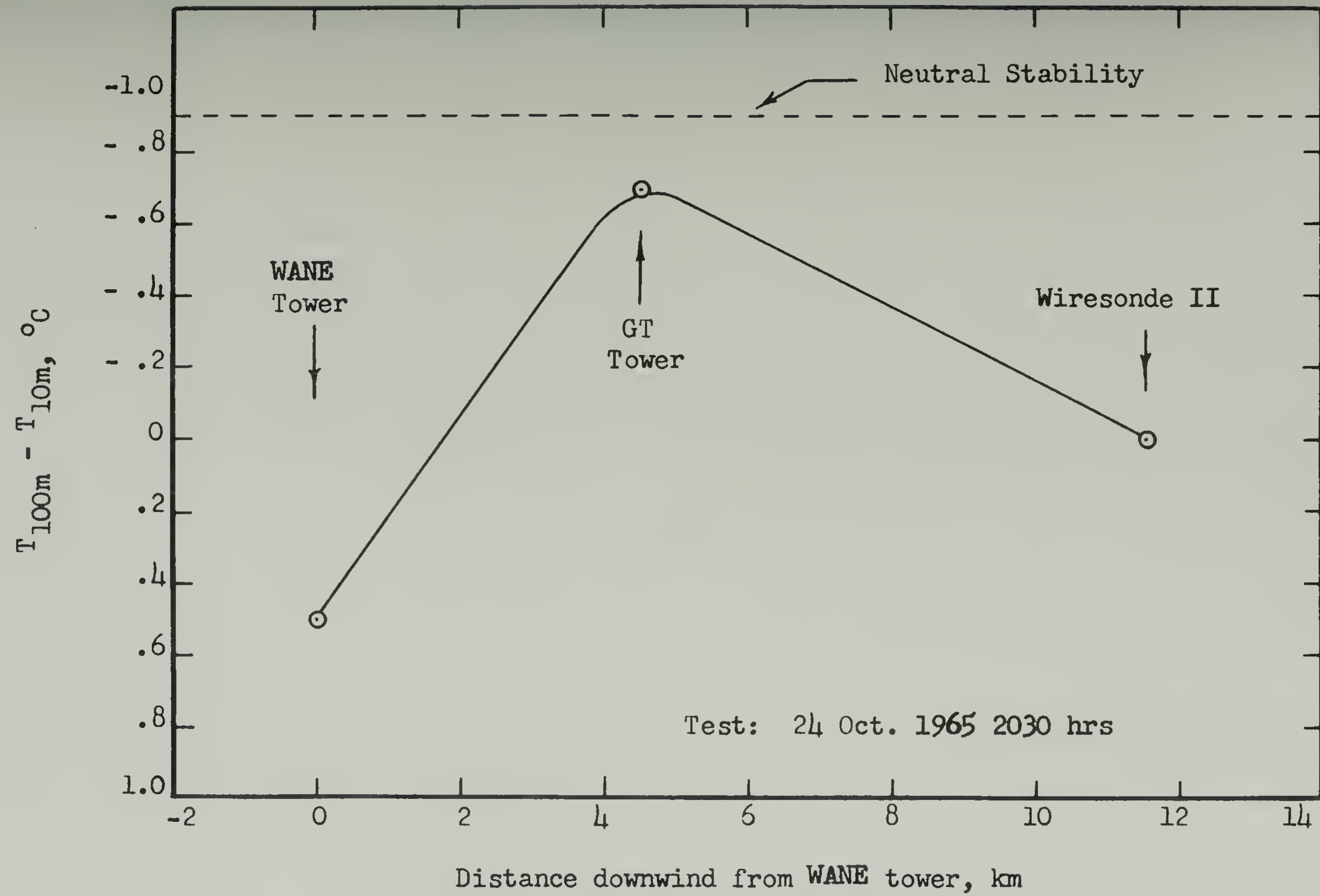

FIGURE 19. EFFECT OF FORT WAYNE HEAT ISLAND ON VERTICAL TEMPERATURE DIFFERENCE

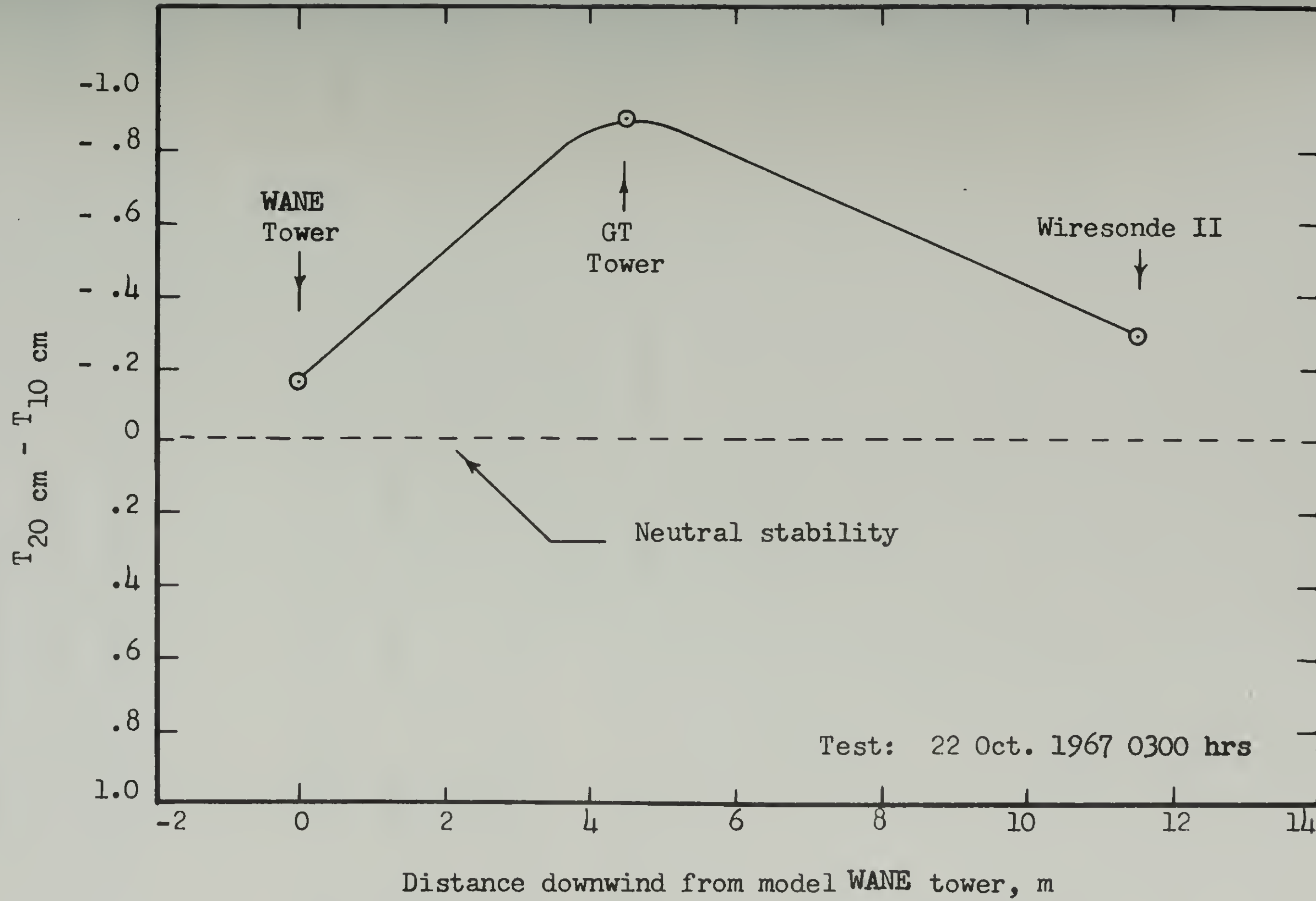

FIGURE 20. EFFECT OF MODEL HEAT ISLAND ON VERTICAL TEMPERATURE DIFFERENCE

the information that was available showed some qualitative results.

The experimental results obtained from the model showed the strong influence of wind speed on the behavior of the model. The effect of wind speed on the ability of the model to distort the vertical temperature profile between 10 and 15 centimeters is shown in Figure 21. The more negative values of $\Delta T_{GT} - \Delta T_{WANE}$ indicate the greater effectiveness of the model in distorting the temperature profile. This figure indicates that the behavior of the model heat island was almost totally dependent on wind speed for the observational periods of this research. This might be expected from the method of selection of observational periods which, for example, reduced the effects of cloud cover and wind direction variation.

In contrast with the model, the prototype revealed a considerably more complex dependence on the meteorological variables and no similar trend could be found from the data.

Although one might have expected the dense structure of the surface elements of the model to appear as a solid object to the wind, the data indicate that even at the lowest level of differential temperature measurement (1 cm to 5 cm) the wind speed exerted a strong influence (Figure 22).

D. Experimental Results

The effect of the urban heat island in making the stable atmosphere of the rural areas unstable has been one of the unresolved factors in the efforts to develop good dispersion estimates. As was mentioned in Chapter V, the prototype profiles selected for modeling

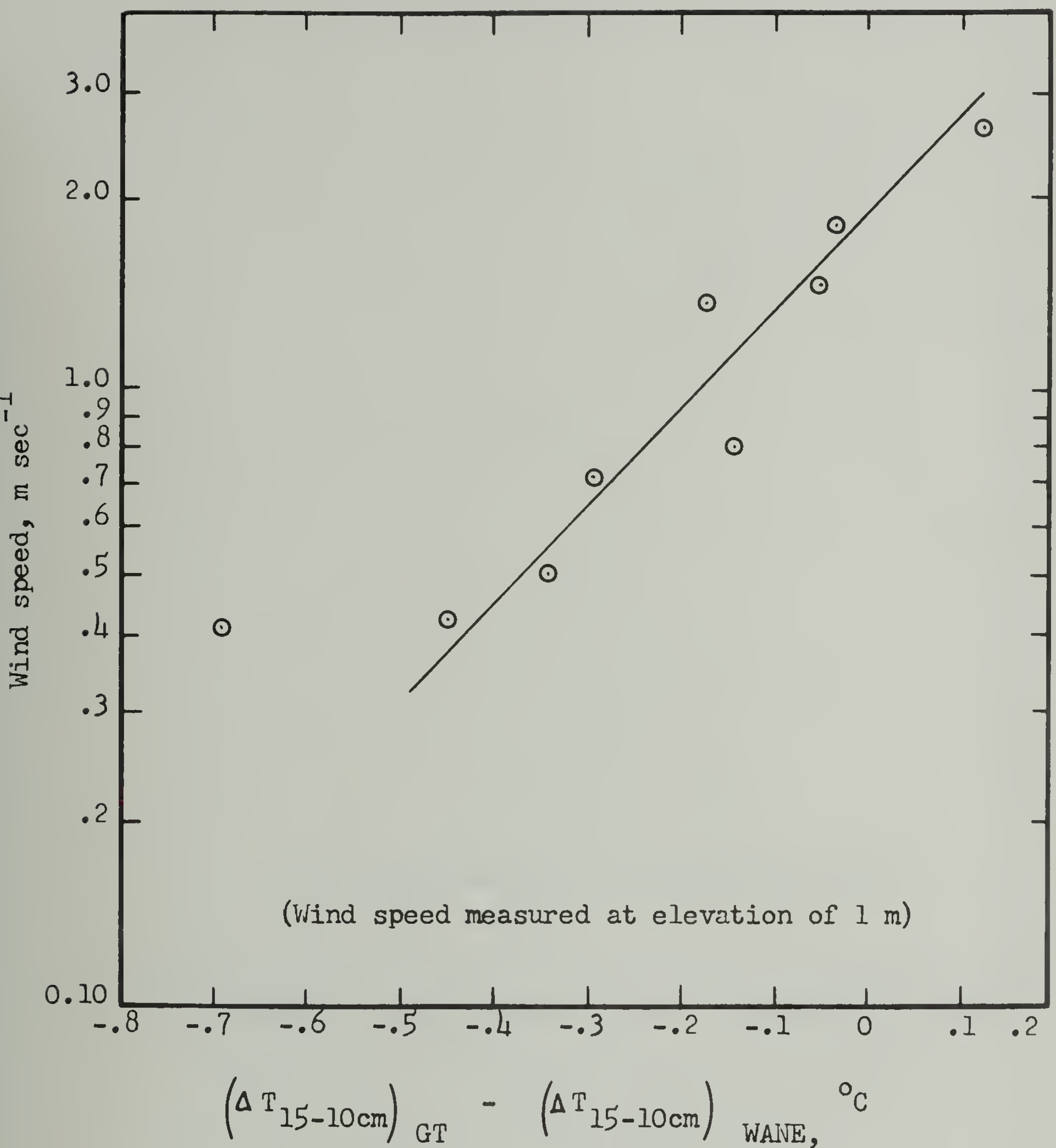

FIGURE 21. EFFECT OF WIND SPEED ON MODEL HEAT ISLAND

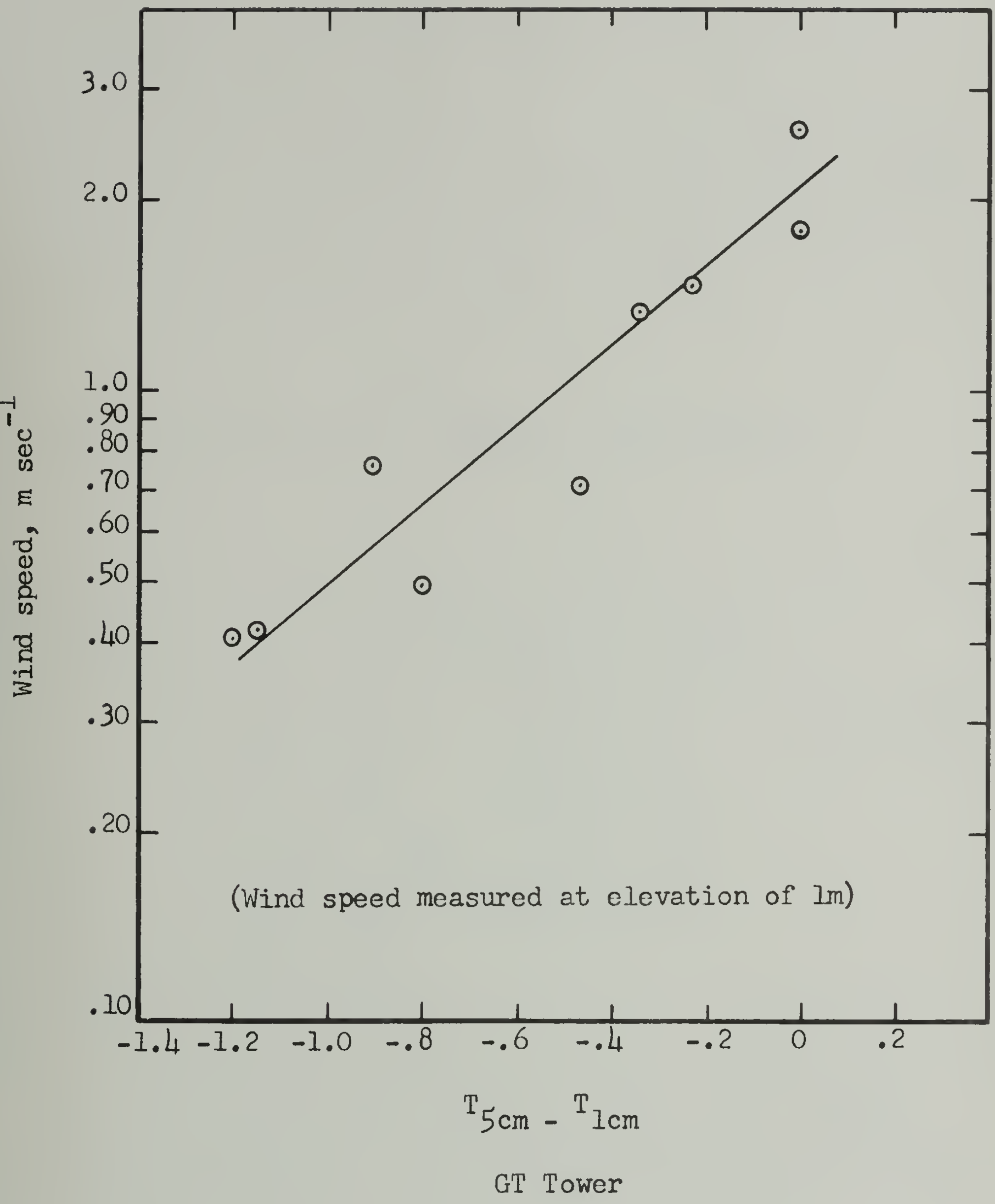

FIGURE 22. EFFECT OF WIND SPEED ON TEMPERATURE DIFFERENTIAL AT MODEL GT TOWER

were those exhibiting stable or near neutral potential temperature lapse rates. Unfortunately only very few prototype profiles met these criteria and those available were not very different from the neutral case. The prototype profiles and those model profiles which were considered for profile correspondence are listed in Table 19.

TABLE 19

PROTOTYPE PROFILES AND COMPARISON MODEL PROFILES

Prototype Profile	Corresponding Model Profiles		
24 Oct. 2000	30 Sept. 2230	12 Oct. 0030	22 Oct. 0300
24 Oct. 2030	12 Oct. 0100	22 Oct. 0300	
24 Oct. 2115	19-20 Oct. 0000	3 Dec. 1700	
26 Oct. 2115	11 Oct. 2100	12 Oct. 0100	
4-5 Feb. 0000	30 Sept. 0300		

Two profile comparisons were selected for more detailed discussion (Figures 23 and 24). The remaining profiles are included as Appendix D.

In determining the dispersion variances σ_y and σ_z, the air pollution meteorologist customarily would like to refer to a plot of temperature difference versus elevation or of potential temperature difference versus elevation. Thus, the graphical method selected for comparison of the profiles was that of plotting the prototype potential

temperature profile and the scaled homologous model potential temperature profile. (It would of course be improper to superimpose all the profiles because it would unrealistically normalize the temperatures at the lower elevations.)

Figure 23 is an example of three prototype profiles and the scaled homologous model profiles. The geometric scale factor chosen to scale the model profiles was 0.001. In this case, the agreement of the model and prototype is exceptionally good for all three profiles. This is typical of the behavior of the system, i.e. if a good correspondence between model and prototype was achieved for one homologous profile, then the other homologous profiles yielded similarly good correspondence.

Figure 24 is an example of the failure of the model system to produce a good estimate of the prototype profiles for the chosen geometric scale factor of 0.001. From the idealistic point of view, the model failed; however, from the practical point of view, there is a strong enough correspondence between the model and prototype to provide an estimate of spatial variation of stability required by the air pollution meteorologist.

The general conclusion drawn from these two figures and those appearing in Appendix D is that it is possible to model the variation of atmospheric stability of an air mass passing over an urban complex. In particular it appears that if one model profile can be "calibrated" to the prototype, as suggested by the workers at Argonne National Laboratories (1967), the other profiles will yield exceptionally good simulation of the stability variation.

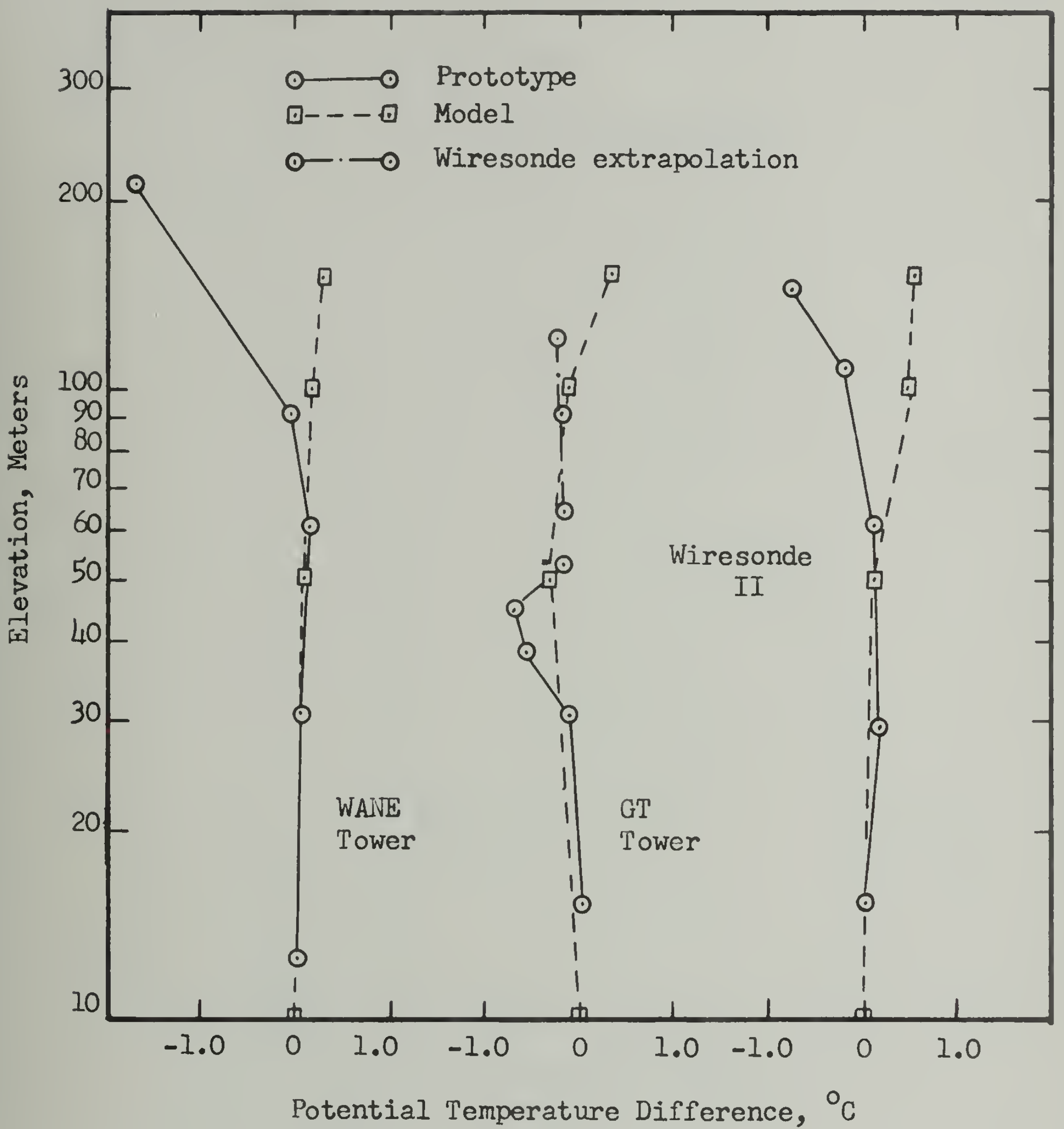

FIGURE 23. PROFILE COMPARISON: PROTOTYPE 24 OCT. 2115 hrs and MODEL 19-20 OCT. 0000 hrs

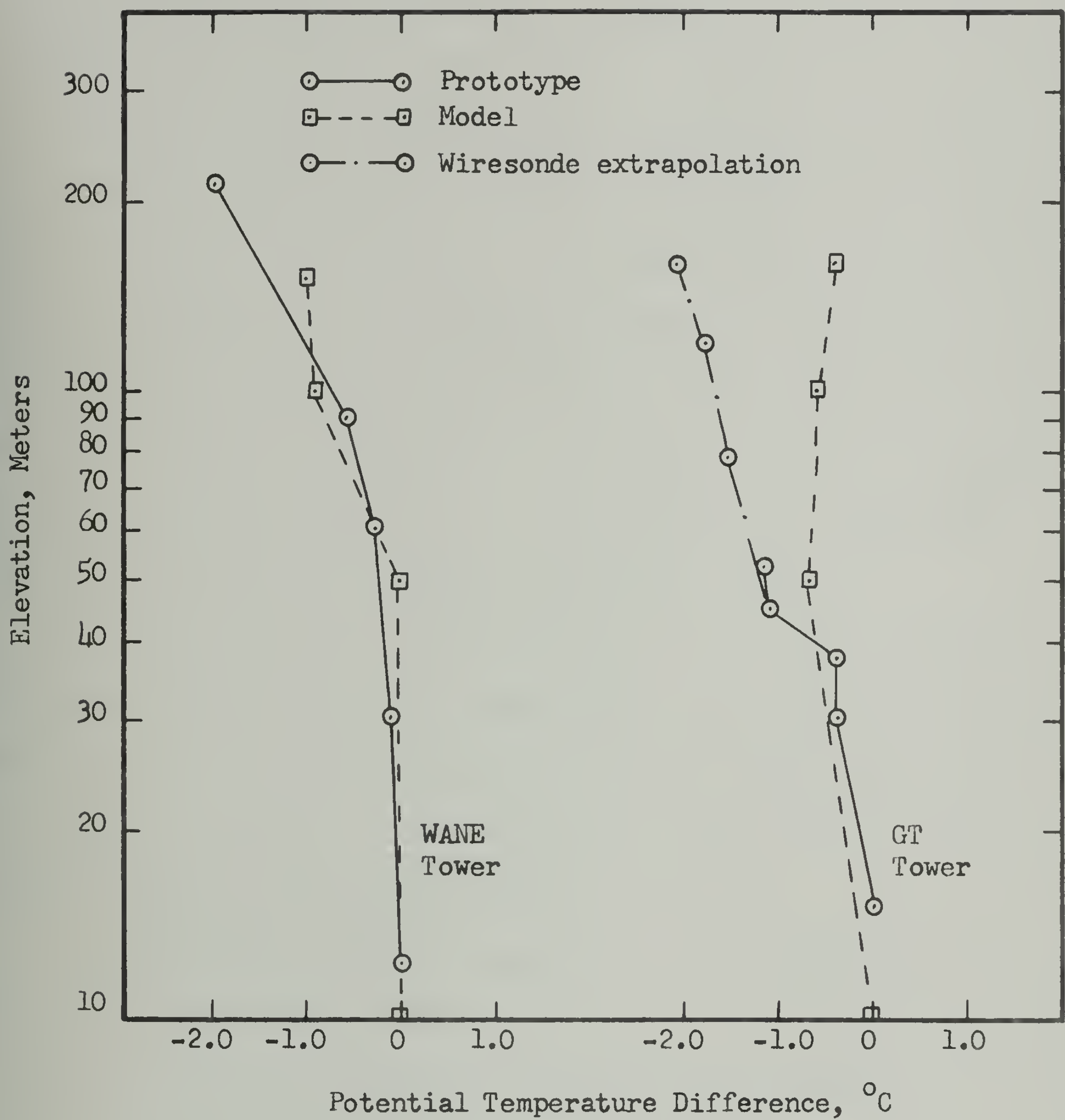

FIGURE 24. PROFILE COMPARISON: PROTOTYPE 26 OCT. 2115 hrs and MODEL 11 OCT. 2100 hrs

In order to attempt a test of the model law, whose validity would make "calibration" more general, a comparison was made between the standard error of the GT model profile in estimating the GT prototype (S_x^2) and the standard error of the scale factor calculated from the model law in estimating the geometric scale factor (S_y^2) which was used in plotting. In other words, it was expected that the failure of the model to idealistically simulate the prototype was due to the inability to select exact scale values of the variables U and H (in contrast to the wind tunnel engineer's control in setting these variables) which would satisfy the model law. The prototype-model comparisons and the standard errors of estimate are listed in Table 20.

A 99.9 percent confidence interval for S_x^2 was constructed (using the "t" distribution) to judge whether or not the first profile comparison (24 Oct. 2000 and 30 Sept. 2230) was in the same population as the rest of the data. On this basis, the first profile was rejected from the analysis of correlation between S_x^2 and S_y^2.

Although the data were admittedly sparce, a correlation analysis was carried out to determine if the behavior of S_x^2 was in any way related to the behavior of S_y^2. The resultant correlation coefficient was 0.61. Ezekeil and Fox (1959) show that this value is significant at the 95 percent confidence level for the sample size used in the computation.

TABLE 20

STANDARD ERRORS OF ESTIMATE

Profiles Compared: Prototype	Model	S_x^2	S_y^2
24 Oct. 2000	30 Sept. 2230	1.15	.053
24 Oct. 2000	12 Oct. 0030	.44	.004
24 Oct. 2000	22 Oct. 0300	.46	.044
24 Oct. 2030	12 Oct. 0100	.28	.336
24 Oct. 2030	22 Oct. 0300	.17	.003
24 Oct. 2115	19-20 Oct. 0000	.01	.005
24 Oct. 2115	3 Dec. 1700	.04	.008
26 Oct. 2115	11 Oct. 2100	.58	.722
26 Oct. 2115	12 Oct. 0100	.51	.689
4-5 Feb. 0000	30 Sept. 0300	.28	.490

CHAPTER VII

SUMMARY DISCUSSION

From the discussions of the energy balance equation it appears that the heat island effect in Fort Wayne is due, primarily, to the heat generated from human activities and the more efficient heat storage properties of the city structure. These two things contribute approximately 30 percent more heat to the urban environment than is available to the rural environment.

The discussions of radiation alteration by the city revealed that only a mist or haze layer would contribute to the urban-rural temperature disparity. Because the atmosphere of Fort Wayne is relatively unpolluted, its radiation characteristics are quite similar to those of the rural environs and thus radiation alteration does not contribute significantly to the heat island effect.

Although it was surmized that 10 percent of the precipitation falling in the urban area was lost to the sewers, one might expect that the increased urban precipitation would compensate this loss. Thus, the expected 10 percent excess energy availability in the city is probably not realized.

It has been shown that it is possible to carry out micrometeorological experiments which model the effect of the heat island on atmospheric stability. For the attempts to model the variation of stability over Fort Wayne, it was shown that, when the model law was satisfied for a geometric scale factor of 0.001, model profiles resulted which were a good estimate of the prototype behavior.

Although the method of designing the scale model is subject to question and certainly requires further investigation, the vertical distortion of the model has not significantly altered the validity of applying the horizontal scale factor.

Although the test of the model law did not explicitly rule out the possibility of other modeling criteria, it was shown that the hypothesized model law could be used to relate model experiments to the prototype.

The ultimate significance of this work is to lend strong support to the possibilities of modeling the meteorological variables governing dispersion in the urban atmosphere.

CHAPTER VIII

CONCLUSIONS

The following conclusions may be drawn from this investigation:

1. The City of Fort Wayne has a heat island effect which is of a comparable order of magnitude to other reported urban heat islands.
2. The primary elements contributing to the heat island effect in Fort Wayne, Indiana are fuel consumption and a heat storage effect which is more efficient than that of the rural environs.
3. The feasibility of using the real atmosphere as a medium in which to conduct meteorological modeling experiments has been explored and shown to have great potential use.
4. For the case of the City of Fort Wayne, Indiana, it has been shown that it is possible to model the effect of the urban heat island on atmospheric stability.
5. A hypothesized model law of the form

$$\frac{K_L K_H}{K_U^3} = 1$$

was shown to be a valid means for examining experiments to model the effect of the urban heat island on stability. A correlation analysis between the error of the model

profiles in estimating the prototype profiles (S_x^2) and the standard error of estimate of the model law (S_y^2) was conducted. The correlation coefficient was 0.61. This correlation coefficient was found to be significant at the 95 percent confidence level.

6. Contrary to expectations, the vertical distortion of the model did not result in a distorted scale factor.

CHAPTER IX

SUGGESTIONS FOR FUTURE WORK

As a consequence of this investigative effort, several questions have been raised which are offered here as suggestions for future work.

The most obvious need with respect to this research is further investigation to confirm the feasibility of modeling urban atmospheres. Experiments carried out at scales of 1:100 and 1:10,000 would help resolve the question of what is "the" characteristic length.

In order to make this work generally applicable, the rationale for the design of the model must be developed. The usefulness and/or necessity for vertical distortion of the model must be established by experiments on element densities of one half and one quarter of that used in these experiments with element heights varying between one half and five times that used in this work.

Consideration should, of course, be given to the applicability of the empirical roughness calculation as well as the "plan ratio" method used in this work for design purposes.

The placement of the heating elements should be above ground in future designs. This will increase the speed and ease of erection of the model as well as allowing for greater flexibility in operation both with the roughness elements and with the power supply.

The general applicability of the empirical roughness length in estimating urban roughness and/or model roughness should be considered because of the finite nature of the roughness discontinuity.

Once the feasibility of this type of modeling has been thoroughly examined, a combined prototype-model study of the most thorough type would be in order. Direct measurements of the modeling parameters should be made in both the model and prototype over a minimum period of one year in order to afford the opportunity to model a wide variety of situations. Of particular interest is the measurement of the variables of the energy balance equation over a sufficient interval (several years) to quantitatively estimate their individual importance to the heat island phenomenon.

The strong dependence of this investigative technique on the weather severly limits the periods of operation. Once the technique has been shown to be valid, serious consideration should be given to the possibility of erecting suitable wind tunnel facilities. The gigantic proportions required for a wind tunnel to model urban atmospheric behavior requires careful economic as well as technical justification, i.e., it may be that considerable funds could be expended to make autogenous simulation more practical at a fraction of the expense of wind tunnel modeling.

The possibilities of the direct application of this modeling technique to area diffusion problems would, of course, be the ultimate perfection of this technique as far as the air pollution meteorologist is concerned.

Many other meteorological situations might be examined by this method of modeling. In particular the cases of localized heating

and cooling such as the valley wind, tropical island "heat mountains" and lake breeze effects all fall into the same class of phenomena as the urban heat island.

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APPENDIX A

DATA FOR CALCULATION OF FORT WAYNE'S THERMAL PROPERTIES

THERMAL CONSTANTS

Material	ρ lb ft^{-3}	C_p Btu lb^{-1} F^{-1}	λ	α	References[a]
Air space, $3\frac{5}{8}$ in.	0.081	0.24	0.01	-	4, 4, 6, -
Asphalt	80	0.22	0.43	0.15	4, 6, 6, 2
Brick facing	130	0.22	0.75	0.35	1, 3, 1, 2
Building paper, $\frac{1}{32}$ in.	50	0.20	0.02	0.14	3, 8, 6, 2
Built-up roof	70	0.20	0.93	-	1, 8, 7, -
Cinder block, 8 in.	11 lb/ft^2	0.20	0.44	-	7, 8, 7, -
Concrete, stone aggregate	150	0.24	0.54	0.35	3, 3, 6, 2
Glass, window	160	0.18	0.61	-	4, 4, 1, -

1. A.S.H.R.A.E. (1961)
2. Beckett (1935)
3. Billington (1952)
4. Hudson (1959)
5. Ingersoll (1948)
6. Perry _et al_.(1963)
7. Calculated value
8. Estimated from other values

[a]References in order from left to right

THERMAL CONSTANTS

Material	ρ lb ft^{-3}	C_p Btu lb^{-1} F^{-1}	λ	α	References[a]
Limestone, crushed	103	0.22	0.54	-	6, 6, 6, -
Paint, white	-	-	-	0.82	-, -, -, 2
Paint, yellow	-	-	-	0.67	-, -, -, 2
Plaster, gypsum	105	0.21	0.47	-	1, 8, 1, -
Shingles, asphalt	70	0.20	0.56	0.15	1, 8, 4, 8
Steel	480	0.12	26.2	-	4, 4, 6, -
Wall board, gypsum	50	0.26	0.09	-	1, 1, 1, -
Wood, pine across grain	34	0.42	0.09	-	6, 4, 6, -

1. A.S.H.R.A.E. (1961)
2. Beckett (1935)
3. Billington (1952)
4. Hudson (1959)
5. Ingersoll (1948)
6. Perry _et al._ (1963)
7. Calculated value
8. Estimated from other values

[a]References in order from left to right

1966 ANNUAL REPORT OF CITY ENGINEER FORT WAYNE[a]

STREETS:	
Total miles	561.16
Asphalt sheet	91.77
Asphaltic concrete	78.54
Brick	20.75
Reinforced concrete	79.08
Plain concrete	87.52
Chip seal	21.66
Macadam binder	33.88
Stabilized hot asphalt	23.55
Total paved	439.43
STATE HIGHWAYS WITHIN CITY LIMITS	
Total miles (reinforced concrete)	52.38
SIDEWALKS	
Total miles	438.25
POPULATION	
Estimated by Plan Commission	179,369
AREA CITY OF FORT WAYNE	40.99 sq. miles
OCCUPIED DWELLINGS	
Estimated by Plan Commission	56,000

[a]Traylor (1967)

HOURLY VARIATIONS OF TRAFFIC
FORT WAYNE, INDIANA[a]
TRAFFIC ENGINEERING DEPARTMENT[b]

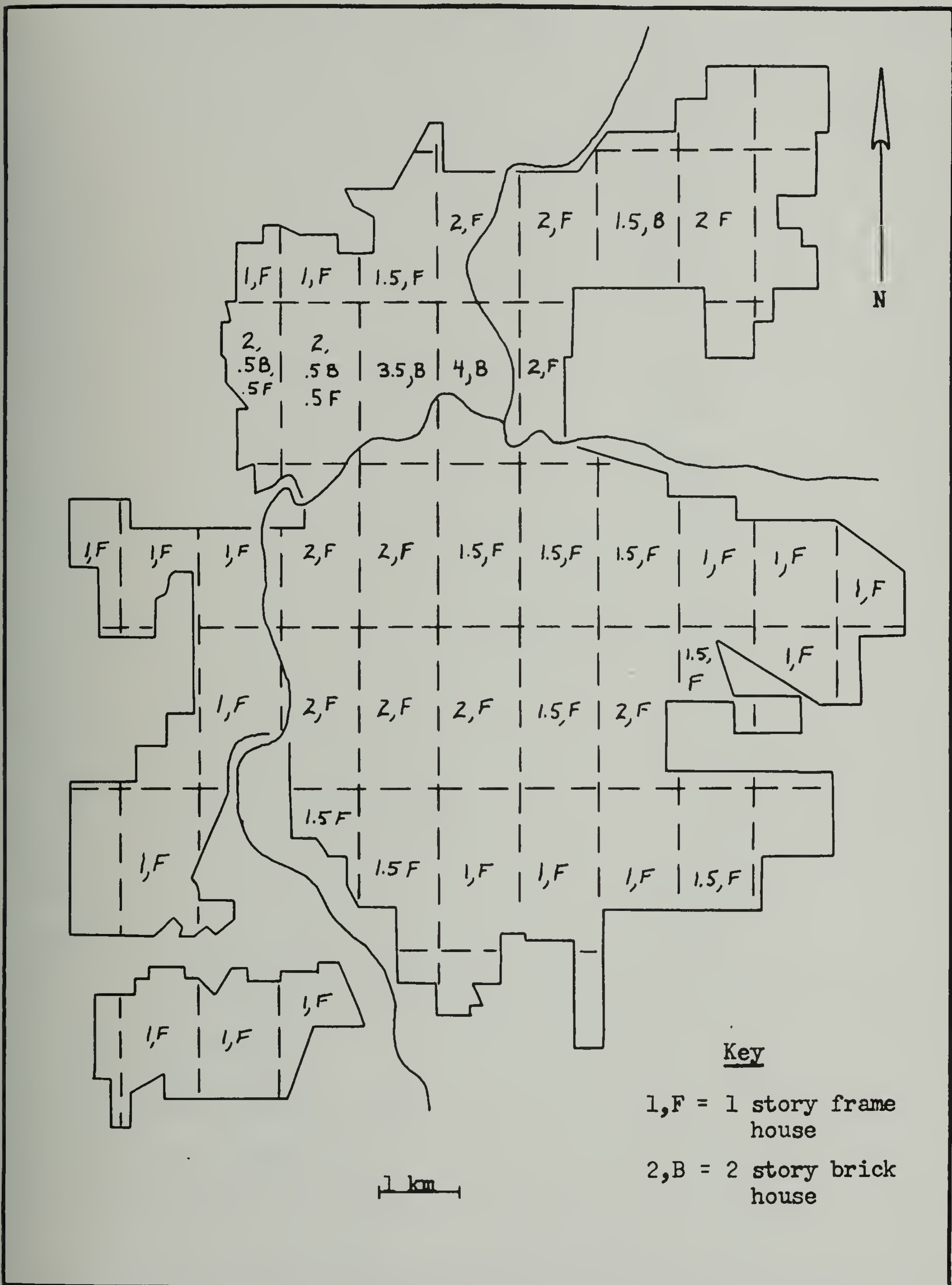
Hour	Residential Primary Artery	Central Business District	State Highway	Industrial Area	Average All Locations
	%	%	%	%	%
			A.M.		
12-1	1.83	1.93	1.29	1.86	1.73
1-2	0.94	1.37	0.65	0.63	0.90
2-3	0.42	0.59	0.38	0.34	0.43
3-4	0.21	0.37	0.35	0.27	0.30
4-5	0.24	0.36	0.33	0.28	0.30
5-6	0.69	0.80	0.99	2.05	1.13
6-7	3.39	2.41	4.39	7.67	4.48
7-8	5.61	5.07	6.17	8.14	6.25
8-9	5.24	5.24	4.51	3.46	4.61
9-10	5.15	5.37	4.46	3.67	4.66
10-11	5.43	5.84	4.63	4.05	4.99
11-12	5.51	5.78	4.98	6.00	5.60
			P.M.		
12-1	5.72	5.52	5.12	5.88	5.56
1-2	5.22	6.05	5.31	4.70	5.32
2-3	4.76	6.17	5.36	5.91	5.55
3-4	6.83	6.99	6.86	9.53	7.55
4-5	7.80	7.80	7.70	7.74	7.76
5-6	7.33	6.68	7.49	6.07	6.89
6-7	5.72	4.96	5.98	4.35	5.25
7-8	6.03	5.38	6.44	4.61	5.62
8-9	5.27	5.17	5.26	4.05	4.94
9-10	4.34	4.04	4.51	2.94	3.96
10-11	3.48	3.37	3.87	3.07	3.45
11-12	2.72	2.72	2.96	2.73	2.78
Aver. Wk. Day Vol.	16,000	14,500	18,000	12,500	15,250

[a]All figures shown hereon have been computed upon the basis of an annual average traffic volume.

[b]From Traylor, 1967.

SURFACE SURVEY: FORT WAYNE, INDIANA

MARCH 1967



NORTHERN INDIANA PUBLIC SERVICE COMPANY
GAS SENDOUT 1965-1966[a]

Date	Sendout[b,c,d]
24 Oct.	50,806
26 Oct.	43,178
8 Nov.	48,762
16 Nov.	53,081
17 Nov.	57,872
29 Nov.	74,098
5 Dec.	54,190
6 Dec.	69,500
6 Jan.	68,124
10 Jan.	85,100
13 Jan.	71,100
23 Jan.	87,821
27 Jan.	93,994
28 Jan.	94,073
29 Jan.	95,448
4 Feb.	87,005

a. From Karch, 1967

b. In thousands of cubic feet

c. Btu rating = 980 Btu ft^{-3}

d. Serving 39,373 residences

APPENDIX B

PROTOTYPE DATA

WANE TOWER TEMPERATURES[a]

Elev. m \ Date	24 Oct. 2000	24 Oct. 2030	24 Oct. 2115	26 Oct. 2115	4-5 Feb. 0000
12.2	3.68	3.30	3.08	7.02	-10.77
30.5	3.76	3.44	3.34	7.07	-10.94
61	3.85	3.75	3.73	7.23	-10.67
91.5	3.76	3.85	3.84	7.22	-10.65
21.3	3.22	3.09	3.35	7.25	-9.20

GT TOWER TEMPERATURES[a]

Elev. m \ Date	24 Oct. 2000	24 Oct. 2030	24 Oct. 2115	26 Oct. 2115	4-5 Feb. 0000
15.2	4.85	3.82	4.17	7.98	-9.61
30.5	4.45	3.47	4.18	7.72	-9.89
38.2	4.56	3.55	3.78	7.85	-9.86
45.6	4.00	2.90	3.73	7.20	-10.54
53.5	4.00	2.96	4.40	7.20	-10.74

[a]Temperatures in degrees Centigrade.

WIRESONDE I TEMPERATURES[a]

Elev. m	24 Oct. 2000	Elev. m	24 Oct. 2030	Elev. m	24 Oct. 2115
61	3.2	64.1	2.8	64	2.2
91.2	2.8	99.2	3.0	119	2.7
116	2.8	125	2.8	153	2.9

Elev. m	26 Oct. 2115
67.2	2.2
119	2.7
149	2.9

[a]Temperatures in degrees Centigrade.

WIRESONDE II TEMPERATURES[a]

Elev. m	24 Oct. 2030	Elev. m	24 Oct. 2115
15.2	2.8	15.2	2.1
27.5	2.8	29	2.5
58	2.8	61	2.8
104	2.8	107	2.9
134	2.8	134	2.9
144	2.6	143	2.6

[a]Temperatures in degree Centigrade.

PILOT BALLOON OBSERVATIONS OF WIND SPEED[a]

Elev. m \ Date	24 Oct. 2000	24 Oct. 2030	24 Oct. 2115	26 Oct. 2115	4-5 Feb. 0000
216	5.0	5.5	5.9	8.8	9.7
414	5.8	6.5	6.7	11.7	11.7
612	6.3	6.3	6.2	12.3	10.8
801	6.2	5.5	5.3	10.8	9.8
990	5.1	4.8	4.7	9.2	9.0
1170	4.4	4.6	4.4	8.6	8.2

[a]Wind Speeds in m sec^{-1}.

APPENDIX C

MODEL DATA

MODEL WANE TOWER TEMPERATURE DIFFERENTIALS[a]

Elev. cm \ Date	30 Sept. 2230	30 Sept. 0300	11 Oct. 2100	12 Oct. 0030	12 Oct. 0100
1-5	-.75	-.96	?	?	?
5-10	-.06	-.15	-.27	-.22	-.32
10-15	-.01	-.04	-.01	-.02	0
15-20	.07	-.07	-.95	-.63	-.55
20-25	.22	-.08	-.06	-.72	-.05
25-50	?	?	.82	.52	.88
50-100	.65	?	.90	.62	.68
100-150	.20	.51	.41	.45	.39

Elev. cm \ Date	19-20 Oct. 0000	22 Oct. 0300	3 Dec. 1700
1-5	-1.65	-1.22	.25
5-10	-.10	-.20	.20
10-15	.10	-.05	.10
15-20	.07	-.12	.20
20-25	.10	-.05	.03
25-50	1.40	1.37	.27
50-100	.80	.60	.55
100-150	.48	.47	.40

[a]Temperatures in degrees Centigrade (Temp. at upper level - Temp. at lower level).

MODEL WIRESONDE II TEMPERATURE DIFFERENTIALS[a]

Elev. cm \ Date	12 Oct. 0100	19-20 Oct. 0000	22 Oct. 0300	3 Dec. 1700
1-5	?	-1.17	-.90	-.17
5-10	.18	.20	-.22	?
10-15	-.20	.15	-.20	.15
15-20	.37	.37	-.10	.25
20-25	-.15	.07	-.30	.03
25-50	.89	1.27	1.15	.37
50-100	.42	1.02	1.45	.55
100-150	.49	.47	?	.35

[a]Temperature in degrees Centigrade (Temp. upper level - Temp. lower level).

MODEL GT TOWER TEMPERATURE DIFFERENTIALS[a]

Elev. cm \ Date	30 Sept. 2230	30 Sept. 0300	11 Oct. 2100	12 Oct. 0030
1-5	-.75	-.95	?	?
5-10	-.65	-.73	-.50	-.73
10-15	-.32	-.41	-.69	-.76
15-20	.07	-.08	.12	-.05
20-25	.29	.10	.17	-.11
25-50	.78	?	.43	?
50-100	.80	?	?	?
100-150	.65	.82	.65	.39

Elev. cm \ Date	12 Oct. 0100	19-20 Oct. 0000	22 Oct. 0300	3 Dec. 1700
1-5	?	-1.20	-1.08	-.13
5-10	-.75	-.70	-.60	-.55
10-15	-.50	-.30	-.55	-.25
15-20	-.08	.15	-.30	.05
20-25	-.17	.50	.22	.20
25-50	.71	1.13	.85	.15
50-100	?	?	?	.65
100-150	.79	.47	.55	.32

[a]Temperature in degrees Centigrade (Temp. upper level - Temp. lower level).

WIND SPEEDS[a]

Elev. m \ Date	30 Sept. 2230	30 Sept. 0300	11 Oct. 2100	12 Oct. 0030
.25	.37	.22	.30	.23
.50	.45	.40	.43	.30
1.0	.54	.61	.66	.46
2.0	.70	.72	.95	.52

Elev. m \ Date	12 Oct. 0100	19-20 Oct. 0000	22 Oct. 0300	3 Dec. 1700
.25	.29	.12	.16	.74
.50	.42	.17	.23	.92
1.0	.63	.37	.48	1.20
2.0	1.13	.48	.93	1.56

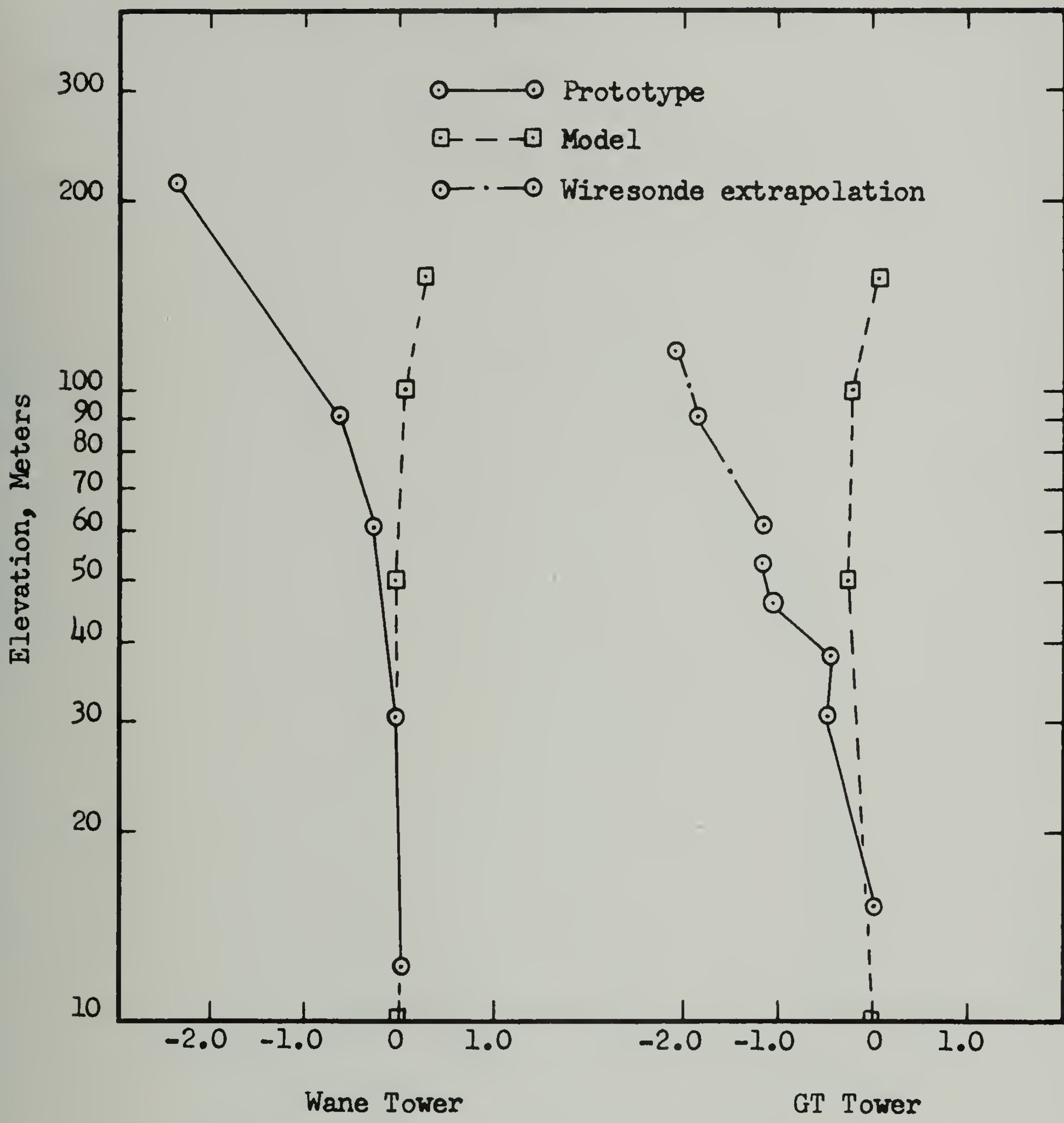
[a]Wind speeds in m sec^{-1}.

APPENDIX D

PROFILE COMPARISONS

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2000 hrs and MODEL 30 SEPT. 2230 hrs



Potential Temperature Difference, °C

$U_p = 5.1 \text{ m sec}^{-1}$ $U_m = .54 \text{ m sec}^{-1}$

$T_p = 278^\circ k$ $T_m = 283^\circ k$

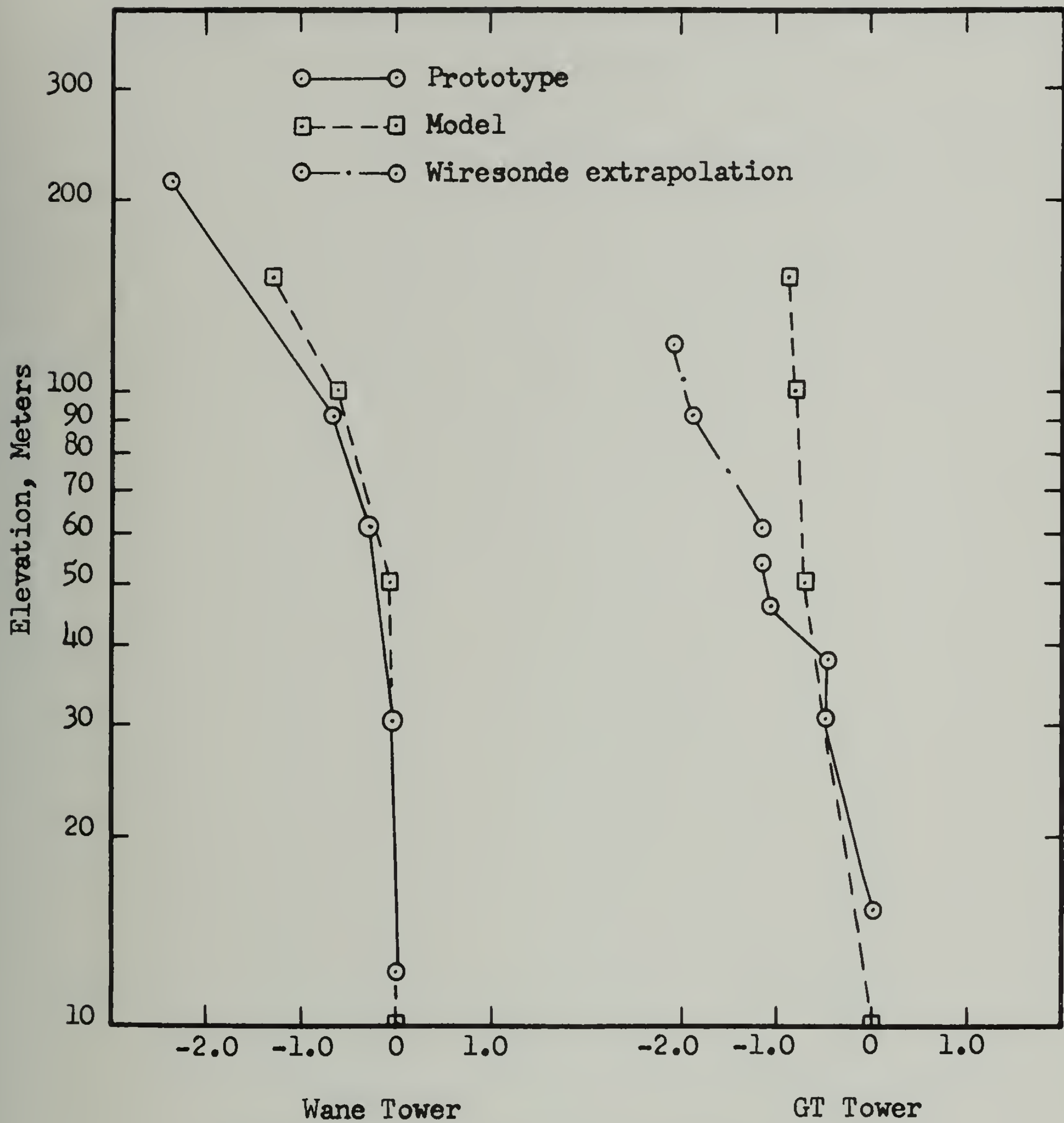
$\rho = 1{,}280 \text{ g m}^{-3}$ $\rho = 1{,}255 \text{ g m}^{-3}$

$H_p = 0.045 \text{ ly min}^{-1}$ $H_m = 0.043 \text{ ly min}^{-1}$

Calculated $K_L = 1.23 \times 10^{-3}$

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2000 hrs and MODEL 12 OCT. 0030



Potential Temperature Profile, °C

$U_p = 5.1 \text{ m sec}^{-1}$ $\quad$ $U_m = .46 \text{ m sec}^{-1}$

$T_p = 278^{\circ}\text{k}$ $\quad$ $T_m = 279^{\circ}\text{k}$

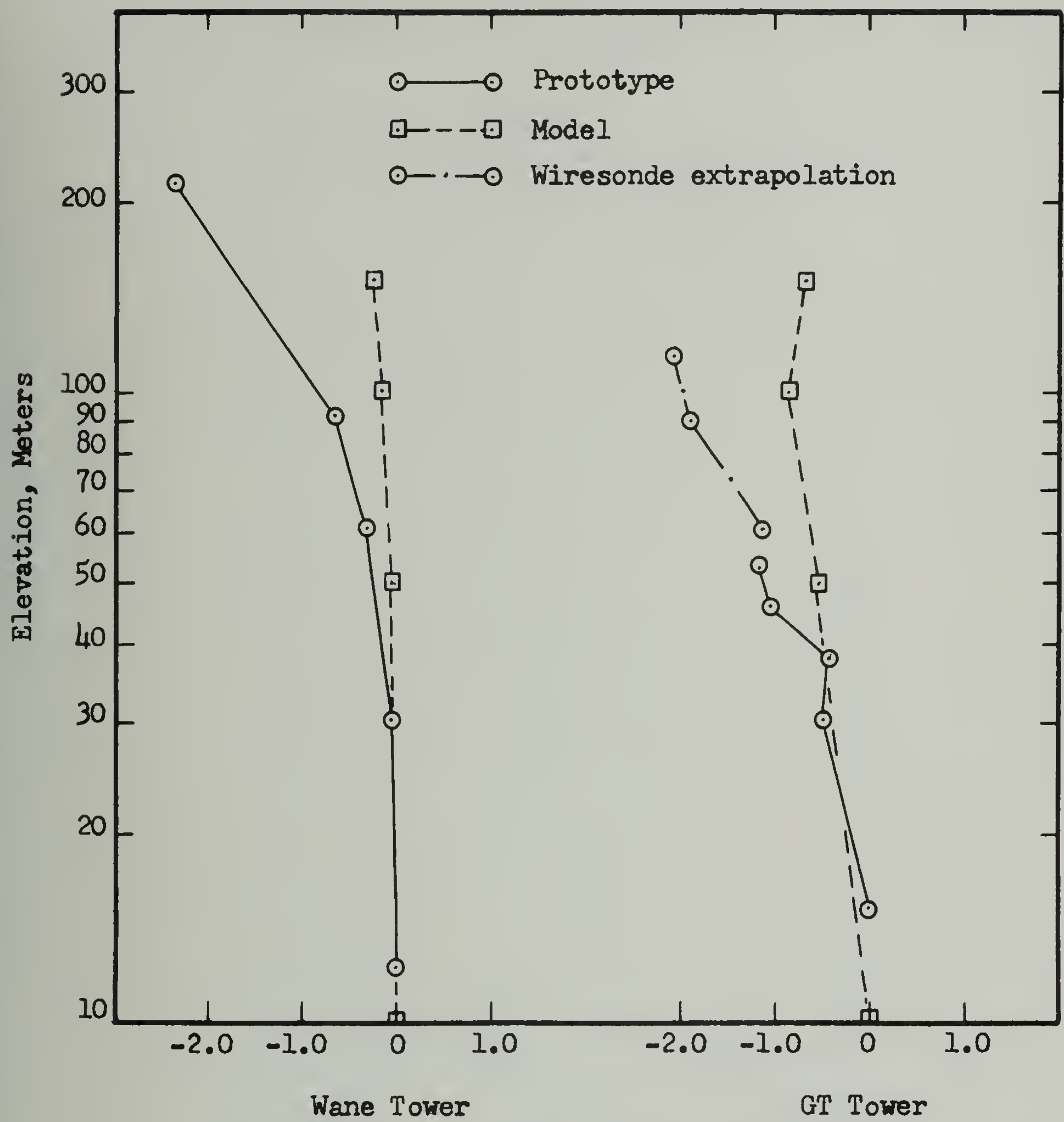
$\rho = 1{,}280 \text{ g m}^{-3}$ $\quad$ $\rho = 1{,}240 \text{ g m}^{-3}$

$H_p = 0.045 \text{ ly min}^{-1}$ $\quad$ $H_m = 0.059 \text{ ly min}^{-1}$

Calculated $K_L = .936 \times 10^{-3}$

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2000 hrs and MODEL 22 OCT. 0300



Potential Temperature Difference, °C

$U_p = 5.1 \text{ m sec}^{-1}$ $\quad$ $U_m = .48 \text{ m sec}^{-1}$

$T_p = 278^{\circ}\text{k}$ $\quad$ $T_m = 278^{\circ}\text{k}$

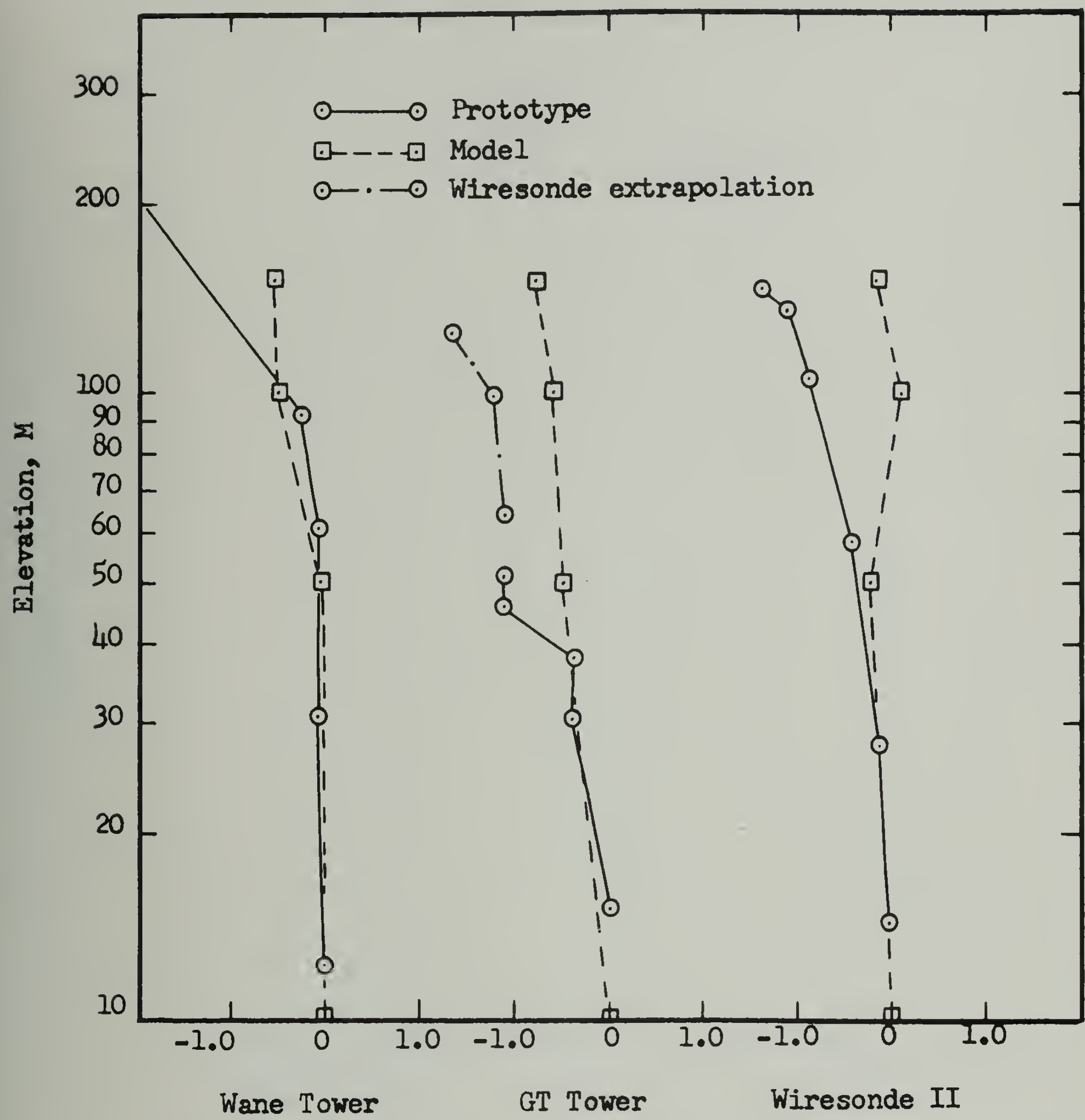
$\rho = 1{,}280 \text{ g m}^{-3}$ $\quad$ $\rho = 1{,}286 \text{ g m}^{-3}$

$H_p = 0.045 \text{ ly min}^{-1}$ $\quad$ $H_m = 0.043 \text{ ly min}^{-1}$

Calculated $K_L = .79 \times 10^{-3}$

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2030 hrs and MODEL 12 OCT. 0100



Potential Temperature Difference, ^{o}C

U_p = 4.8 m sec^{-1} U_m = 0.63 m sec

T_p = $277^{o}k$ T_m = $277^{o}k$

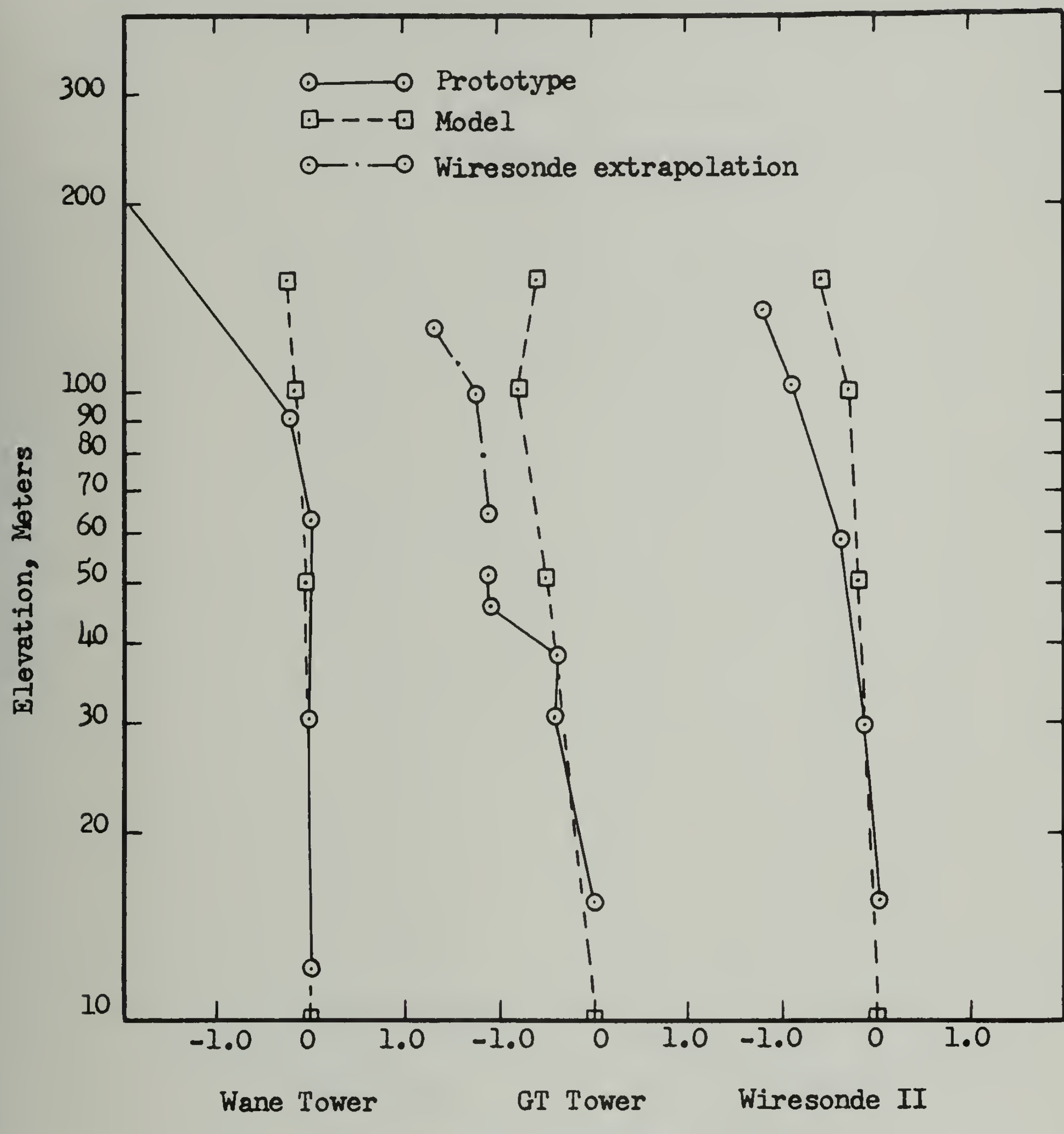
ρ = 1,287 g m^{-3} ρ = 1,270 g m^{-3}

H_p = 0.041 ly min^{-1} H_m = 0.059 ly min^{-1}

Calculated $K_L = 1.58 \times 10^{-3}$

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2030 hrs and MODEL 22 OCT. 0300 hrs



Potential Temperature Difference, $^{\circ}C$

$U_p = 4.8 \text{ m sec}^{-1}$ $\quad$ $U_m = 0.48 \text{ m sec}^{-1}$

$T_p = 277^{\circ}K$ $\quad$ $T_m = 278^{\circ}K$

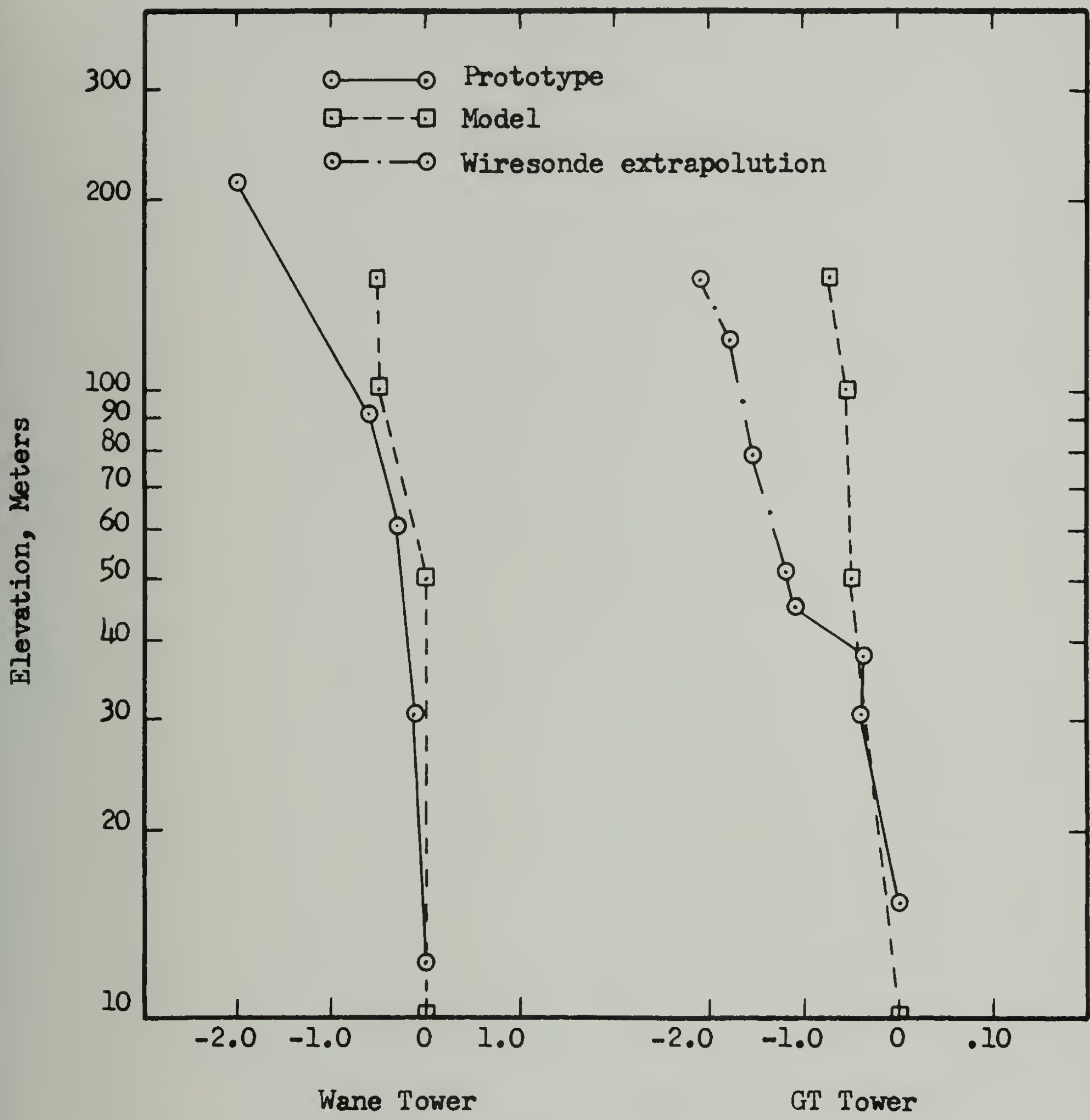
$\rho = 1{,}287 \text{ g m}^{-3}$ $\quad$ $\rho = 1{,}286 \text{ g m}^{-3}$

$H_p = 0.41 \text{ ly min}^{-1}$ $\quad$ $H_m = 0.043 \text{ ly min}^{-1}$

Calculated $K_L = .945 \times 10^{-3}$

PROFILE COMPARISON

PROTOTYPE 26 OCT. 2115 hrs and MODEL 12 OCT. 0100



Potential Temperature Difference, °C

U_p = 9.2 m sec^{-1} U_m = .63 m sec^{-1}

T_p = 281°K T_m = 277°K

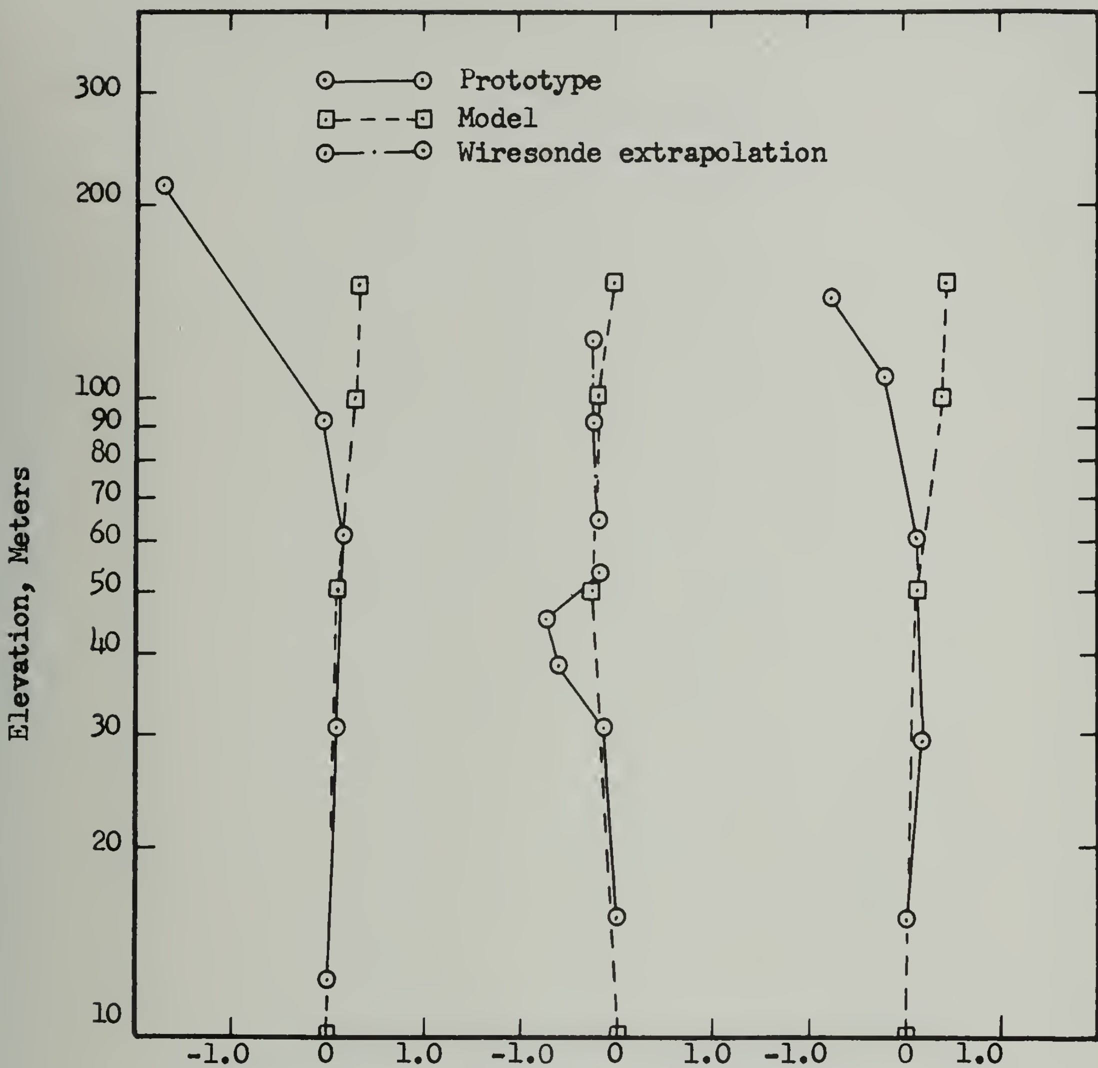
ρ = 1,265 g m^{-3} ρ = 1,270 g m^{-3}

H_p = .027 ly min^{-1} H_m = .059 ly min^{-1}

Calculated K_L = .145 x 10^{-3}

PROFILE COMPARISON

PROTOTYPE 24 OCT. 2115 hrs and MODEL 3 DEC. 1700 hrs



Potential Temperature Difference, °C

U_p = 4.7 m sec^{-1} U_m = 1.2 m sec

T_p = 277°K T_m = 263°K

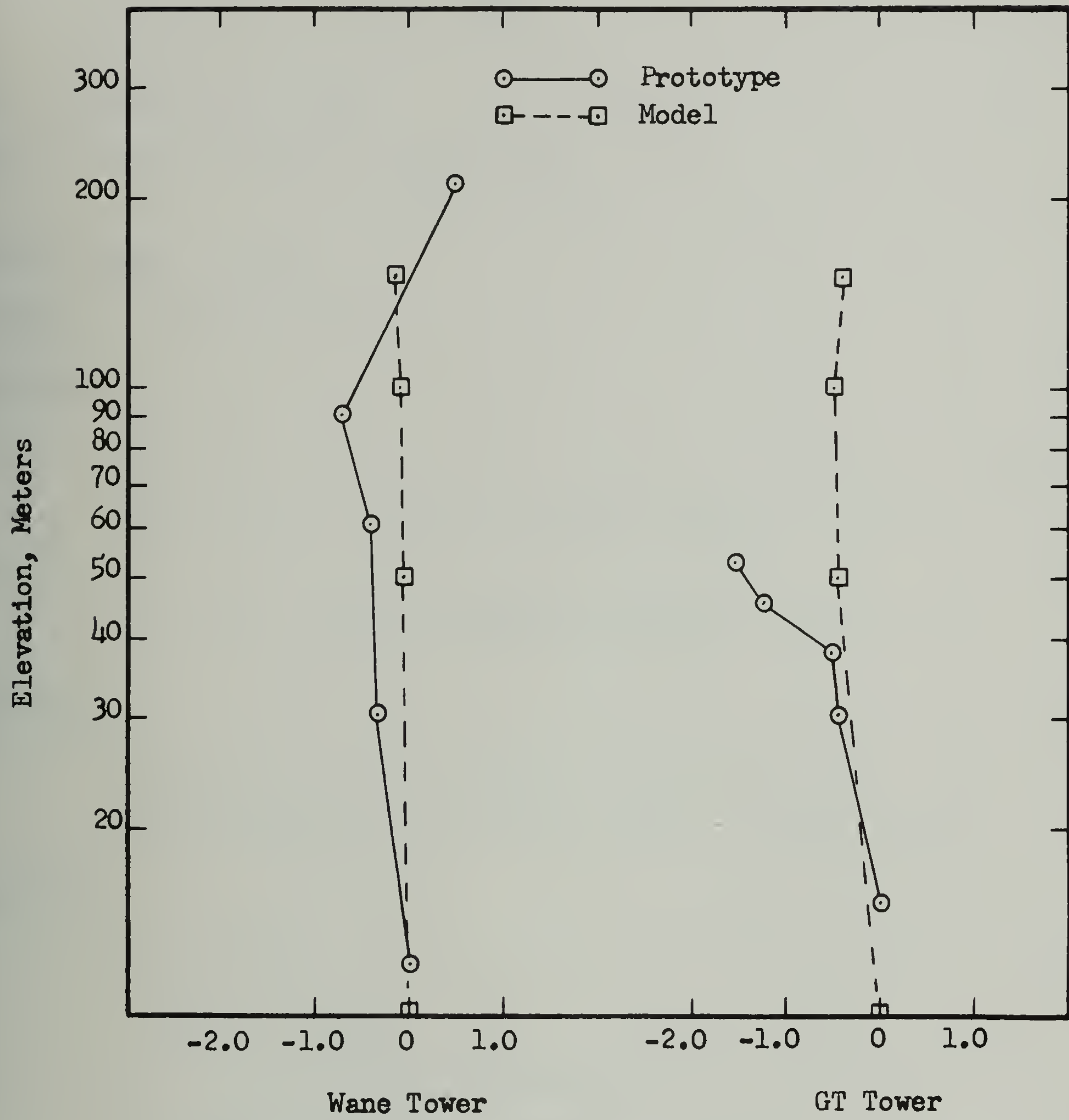
ρ = 1,285 g m^{-3} ρ = 1,355 g m^{-3}

H_p = 0.041 ly min^{-1} H_m = 0.620 ly min^{-1}

Calculated K_L = 1.09 x 10^{-3}

PROFILE COMPARISON

PROTOTYPE 4-5 FEB. 0000 hrs and MODEL 30 SEPT. 0300



Potential Temperature Difference, ^{o}C

$U_p = 9.0$ m sec^{-1} $\quad$ $U_m = .61$ m sec^{-1}

$T_p = 283^{o}K$ $\quad$ $T_m = 281^{o}K$

$\rho = 1,357$ g m^{-3} $\quad$ $\rho = 1,256$ g m^{-3}

$H_p = .034$ ly min^{-1} $\quad$ $H_m = .032$ ly min^{-1}

Calculated $K_1 = .305 \times 10^{-3}$

VITA

Name: Mackenzie Leo Davis

Date and Place of Birth: 13 August 1941
Brooklyn, New York

Marital Status: Married

Children: 1 Daughter age 5

Education:

June 1959 - Graduated from High School, Metuchen, New Jersey

February 1964 - B.S., Civil Engineering, University of Illinois, Urbana, Illinois

June 1965 - M.S., Sanitary Engineering, University of Illinois, Urbana, Illinois

Employment:

1964 University of Illinois, Research Assistant

1967 University of Illinois, Instructor (unsalaried)

Societies:

Chi Epsilon

Society of Sigma Xi

Air Pollution Control Association

American Meteorological Society